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Title **Structure of the Hawke's Bay Forearc Basin and North Island Shear Belt, eastern North Island, New Zealand**

Operator

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Summary

This report describes the broad structure of the forearc basin in Central Hawke's Bay, provides descriptive details about many of the faults and folds and interprets the timing of formation of these structures. The structures are illustrated on 1: 50 000 geological maps (Bland and Kamp 2014) and four regional cross-sections (Enclosure 1). The North Island Shear Belt (NISB) encompasses a series of sub-parallel reverse and oblique-slip faults lying along the western margin of the basin. We infer no more than 10 km dextral offset on Ruahine Fault and a few hundred metres on Mohaka Fault, and their formation during the Late Pliocene (3.0 – 2.6 Ma). This was preceded by regional tilting along the western basin margin from c. 4.7 Ma. The south-eastern margin of the basin has been offset by dip-slip reverse faults and uplifted through growth of the inboard margin of the accretionary wedge formed within the Hikurangi margin.

Kamp, P.J.J. and Bland, K.J. 2014: Structure of the Hawke's Bay Forearc Basin and North Island Shear Belt, eastern North Island, New Zealand Ministry of Business, Innovation and Employment, New Zealand, unpublished Petroleum Report PR4884, 36 p.

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Introduction

A principal forearc basin is an element of the ocean-continent subduction zone in eastern North Island where it is known as the Hikurangi margin (Figs 1, 2). The forearc basin is best developed in the Hawke's Bay sector of Eastern North Island. This area has recently been geologically mapped at high resolution enabling reproduction at 1: 50 000 scale (Bland and Kamp 2014, Enclosure 4, Map Sheets 1-6) (Fig. 3). The stratigraphic fill of this basin, as exposed in outcrop and encountered in exploration drill holes, has also been described in two New Zealand Petroleum and Minerals PR Reports (Bland et al. 2007; Kamp et al. 2007). The age of the basin as a forearc basin probably dates from the Late Miocene (Te Haroto Formation, Lower Tongaporutuan c. 11 Ma) and its development overprinted an earlier basin fill. The basin and its bounding highs presently have a strong NE-SW structural grain, which probably developed during the evolution of the forearc basin and especially during its later stages.

The purpose of this report is to describe the structure of the forearc basin in central Hawke's Bay and the timing of formation of these structures. All of the structures appear on the new geological maps for central Hawke's Bay (Bland and Kamp 2014). Regional structural cross-sections across parts of the basin are reproduced in Enclosure 1.

The information presented here builds on earlier studies of the structure of the region, especially those by Cashman et al. (1992), Erdman and Kelsey (1992), Beanland (1995), Beanland and Haines (1998), and Beanland et al. (1998). Beanland (1995) was chiefly concerned with the character of the North Island Shear Belt (NISB), which is a zone in western parts of the map area where strain is expressed in a series of dip-slip and strike-slip (more inboard position) faults. Cashman et al. (1992) and Erdman and Kelsey (1992) examined strain partitioning across southern parts of the map area between the NISB and the inboard part of the accretionary wedge. Structural elements within Esk Catchment were documented by Leith (2003), and those of middle reaches of the Mohaka River - Te Hoe River confluence were described by Cutten (1994).

Structural overview

The forearc basin is bounded to the east by the inboard part of an uplifted and semi-emergent accretionary wedge and on its western side by an elevated fault-bounded frontal ridge underlain by indurated Mesozoic basement (Fig. 2) (Enclosure 1).

The frontal basement ridge is marked on its eastern side by a zone of dip-slip and dextral oblique-slip faults collectively known as the North Island Shear Belt (NISB). The more major faults in this zone include the Ruahine and Mohaka faults, which align with the Wellington Fault to the south (Fig. 3). A feature of the structure of the western margin of the forearc basin is that the regional strike of the basin fill is more easterly than the strike of the oblique-slip fault system, meaning that the faults truncate progressively younger parts of the succession to the south and to a substantially greater degree (Enclosure 1, Cross-section D-D'). Most of this deformation and associated uplift of the frontal ridge occurred during the Pleistocene, involving Late Pliocene marine strata. On the eastern margin of the basin the accretionary wedge developed during the Late Miocene – Pleistocene, partially damming the eastern margin of the basin. This inboard part of the wedge is developed above sea level south of Cape Kidnappers (Fig. 4).

Within the map area we identify four structural domains following the approach of Cashman et al. (1992) and Beanland et al. (1998) (Fig. 5). Each domain reflects a different style and degree of deformation. From west to east they are (i) Axial Range Domain, (ii) Range Front Contractional Domain, (iii) Central Forearc Basin Domain, and (iv), the Eastern Contractional Domain. The overall structure of the forearc basin is illustrated in a series of 1:1 cross-sections across different parts of the basin (Enclosure 1).

Cross-section A-A'

A north-south section (Enclosure 1) shows a broadly conformable Miocene succession in the north (overlying basement in the west) between Mohaka River and the crest of Maungaharuru

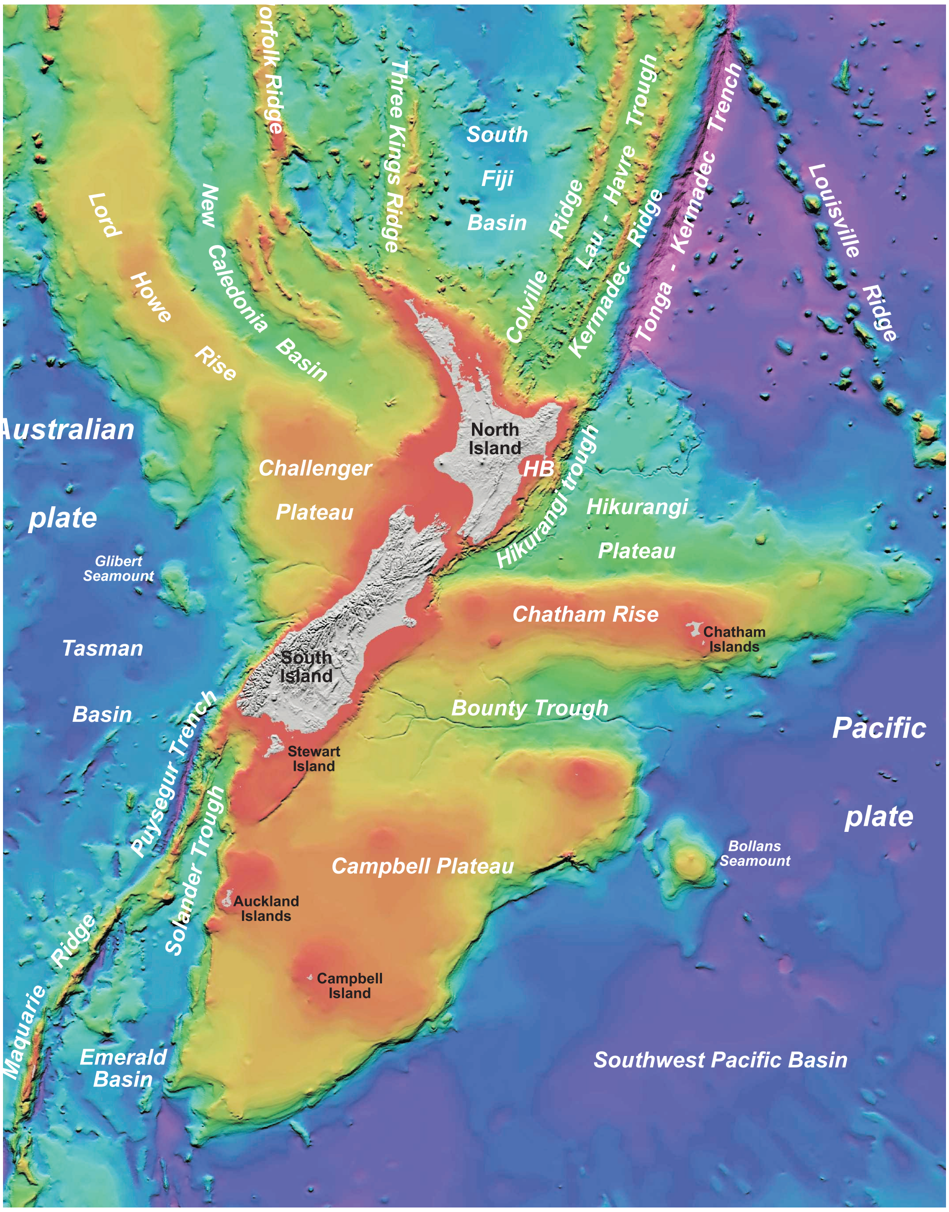


Fig. 1: Map of the New Zealand subcontinent showing the main bathymetric and morphologic features within it. HB, Hawke Bay. This image is the NIWA Undersea New Zealand map.

Range (at Pohokura Saddle) dipping southeast at about 20°. There is a measureable decrease in dip upwards through Titiokura Formation indicative of synsedimentary tilting near the basin margin, requiring concurrent Upper Opoitian uplift of the area to the northwest of the cross-section line. Dips steepen across Rangiora Fault, and within the Tangoio Block dips in shelf marine beds are only a few degrees SE, indicating that the contemporary shoreline must have lain east of Maungaharuru Range. Within the central parts of the basin dips are 2-4° and variably affected by subtle anticlines and synclines (Matapiro Syncline, Taradale Anticline). Between Hedgeley Road and Seafield Road the variably sandy L. Pliocene to E. Pleistocene Pohue Formation to Esk Mudstone succession is shown to make a facies transition into Taradale Mudstone (illustrated more gradually than is shown to be the case in cross-section A-A'). South of Hastings the beds have dips up to 20° to the northwest involving limestone formations. These units transition in the subsurface into terrigenous mudstone involving Mangatoro Formation (E. Pliocene, Opoitian) and Taradale Mudstone (mid-Pliocene, Waipipian – E. Pleistocene, Nukumaruan). Mangaheia Group is underlain by Late Miocene mudstone and flysch of Makara Basin, considered to have accumulated as an accretionary slope basin formed within the accretionary wedge (Pettinga, 1982).

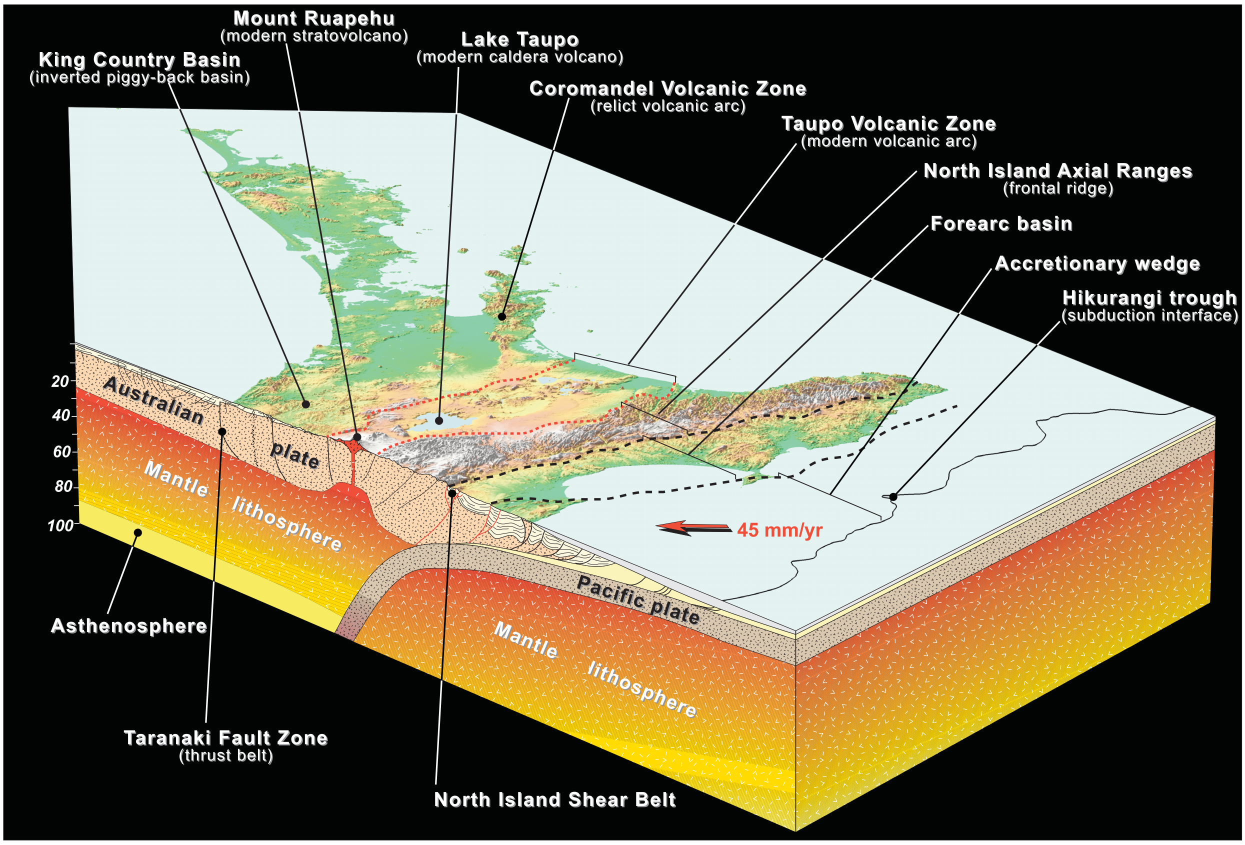


Fig. 2 : Illustration of the tectonic setting of eastern North Island, New Zealand, from central Hawke's Bay and north.

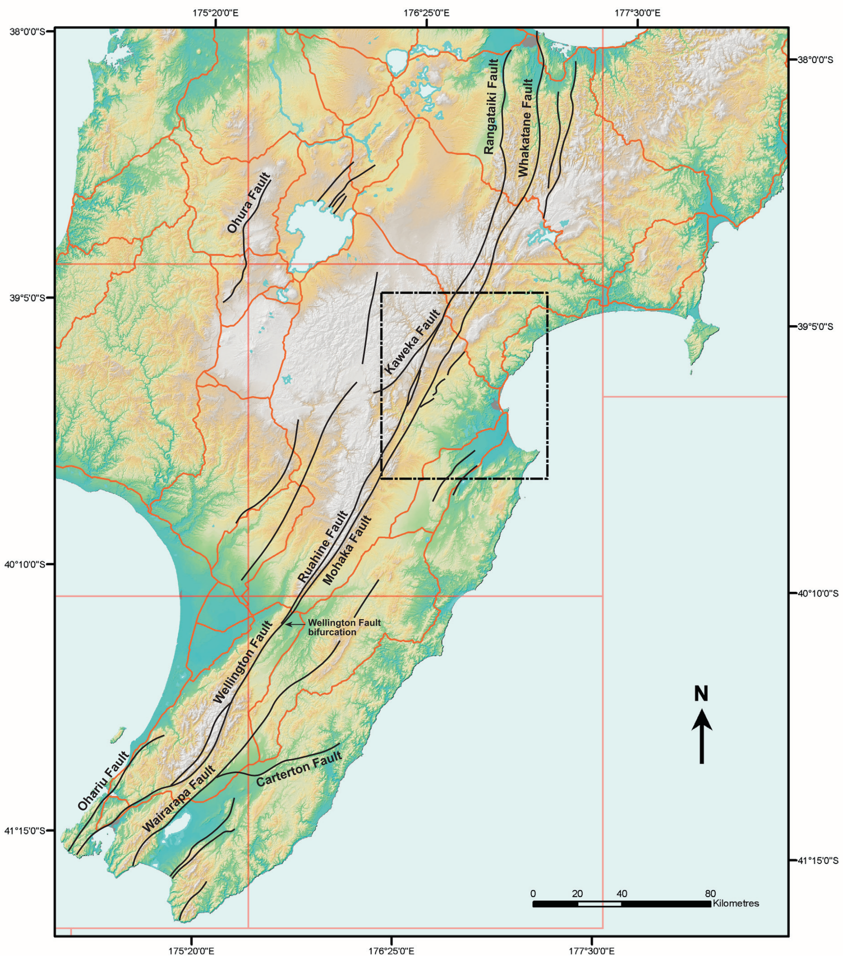


Fig. 3 : The extent of major faults in southern and central North Island are shown. Note that Wellington Fault divides into Ruahine and Mohaka faults. The box outlines the part of central Hawke's Bay geologically mapped by Bland and Kamp (2014).

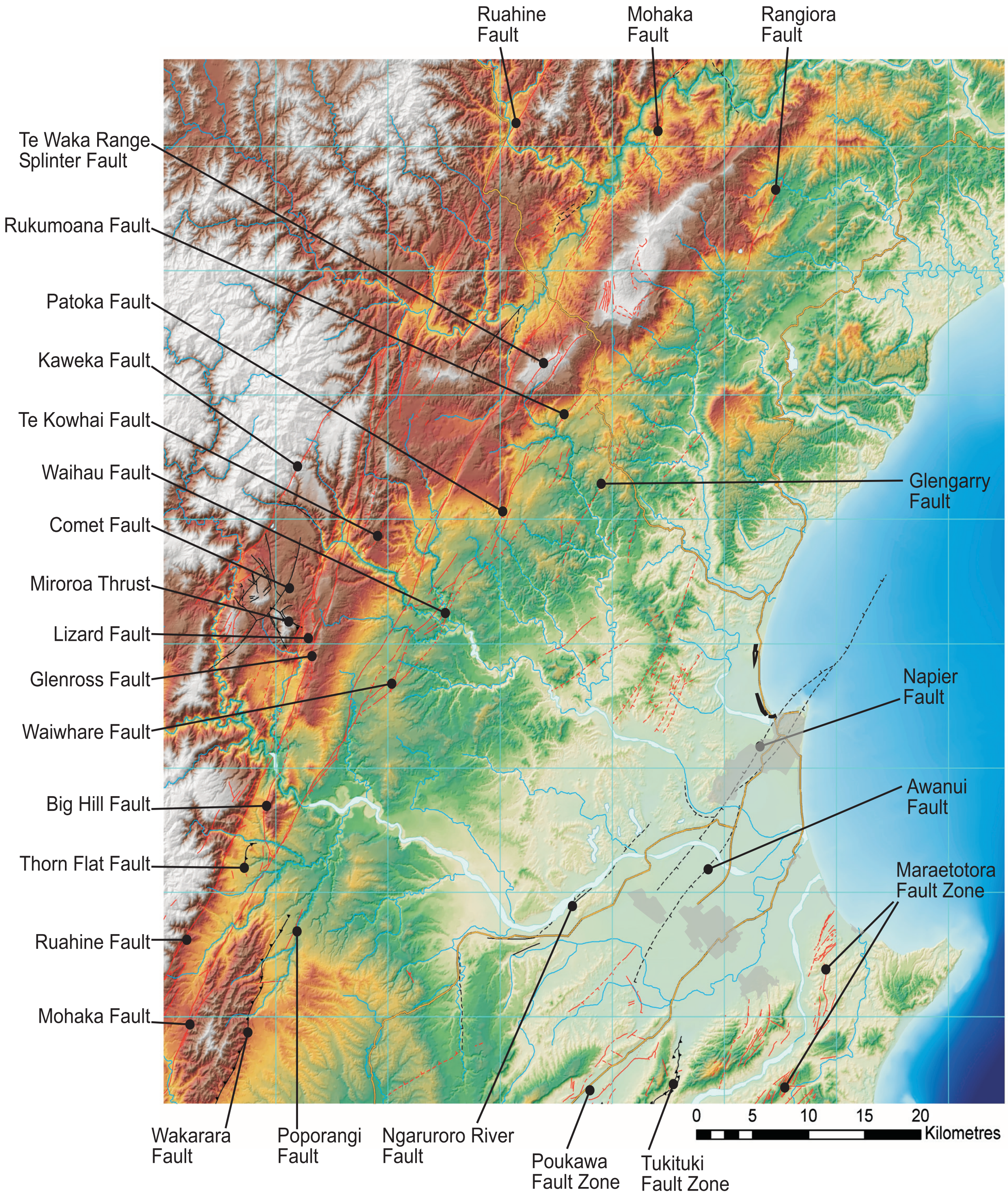


Fig. 4: Locations of major faults and fault zones in the map area. Red lines mark known or inferred active faults; black lines mark other faults. Note the northeast-southwest structural grain. The grid lines are at 10 km spacing from the NZMS 260 series. Residential areas are shown as grey polygons.

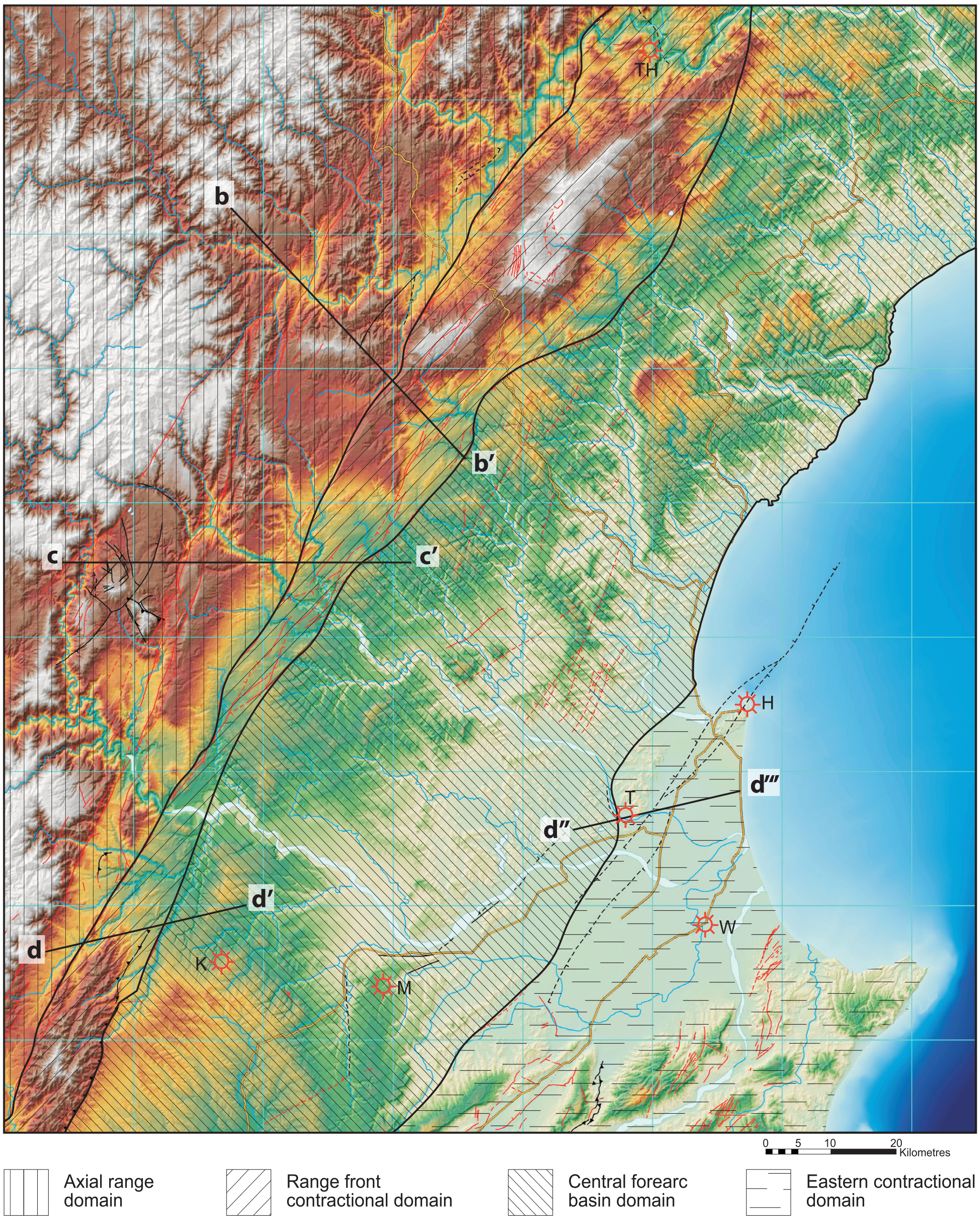


Fig. 5: The extent of four structural domains within the forearc region described in this report. Note transect lines b-b' through d-d' in Figs 9, 10, 14 and 17. The location of hydrocarbon exploration holes are marked by red wheel symbols: TH, Te Hoe-1; K, Kereru-1; M, Mason Ridge-1; H, Hukarere-1; T, Taradale-1; and W, Whakatu-1.

Cross-section B-B'

Cross-section B-B' (Enclosure 1; Fig. 5) is oriented NW-SE parallel to State Highway 5 but south of it (Enclosure 1) (Bland and Kamp 2014, Enclosure 4, Map Sheets 1,3 & 4). At the NW end of this section basement is exposed at the surface together with outliers of the Neogene succession. The oldest cover rocks west of Ruahine Fault are Upper Opoitian (Early Pliocene) Pakaututu Formation (Bland and Kamp 2014, Enclosure 4, Map Sheet 1) and it is inferred that younger parts of the succession have been eroded. Between Ruahine Fault and Mohaka Fault, Tongaporutuan sandstone mapped as Te Ipuohape Sandstone Member onlaps basement. In the vicinity of the cross-section Te Ipuohape Sandstone Member last occurs at the surface, thinning from 100 m to 40 m thick over a few kilometres to the south within the fault block. This sandstone is unconformably overlain by Pakaututu Formation, which in turn is overlain by Puketitiri Formation. South of the cross-section line, Te Waka Formation unconformably overlies Puketitiri Formation. East of Mohaka Fault and into the axis of the forearc basin a more complete Neogene succession occurs. The occurrence of Tongaporutuan sedimentary rocks in the subsurface (Te Ipuohape Sandstone Member and Rakaiita Siltstone Member) is inferred from outcrop along and to the north of the section line (Bland and Kamp 2014, Enclosure 4, Map Sheets 1 & 3). Up to 160 m of Mokonui Sandstone (Upper Kapitean and Lower Opoitian, L. Miocene – E. Pliocene) is exposed immediately east of Mohaka Fault, overlain unconformably by Te Waka Formation (Mangapanian, L. Pliocene) forming Maniaroa Range and Te Waka Range. The intervening formations (Pakaututu Formation and Puketitiri Formation) were eroded in this unconformity, although an age equivalent unit (Titiokura Formation) truncated by erosion is inferred west of Patoka Fault based on its occurrence in outcrop on The Gorges Station (Map Sheet 3). This implies that the timing of erosion is mid- to Late Pliocene immediately before accumulation of Te Waka Formation and this may date the initiation of Late Cenozoic displacement on Mohaka Fault in this area.

West of Potaka Fault to the axis of the forearc basin a conformable succession of Late Miocene to Early Pleistocene (Kaiwaka Formation) units is inferred with minor offset on reverse faults. As for section line A-A', the dip of beds progressively shallows up through the succession, this fanning of dips indicating uplift in the west concurrent with Pliocene sedimentation in the basin axis to the east. Based on the mapping of outcrop along the western margin, basement is reasonably inferred to underlie the Late Miocene (Tongaporutuan) units east of Mohaka Fault, which infers that basement was gently being uplifted in the northwestern part of the map area; that is, despite the numerous late Neogene faults offsetting basement and the late Neogene succession, broad upwarping of basement had a more profound influence on development of the basin and its structure in the northwest than post depositional faulting (e.g. offset on Ruahine and Mohaka faults). It is likely that Paleogene units underlie the Late Miocene units in the more axial parts of the forearc basin, but there is no subsurface information to constrain the age and distribution of such units along the section line.

Cross-section C-C'

Cross-section C-C' (Enclosure 1; c-c' in Fig. 5) is oriented west-east through Kuripapango on the Napier-Taihape road and Kaweka State Forest Park (Bland and Kamp 2014, Enclosure 4, Map Sheets 3 and 4). The broad structure exhibited in the section line is similar to that in line B-B': basement is exposed at the surface in the west with several fault bound outliers of cover rocks, and in the east basement gently dips to the east beneath the Late Miocene and Pliocene forearc basin succession (Enclosure 1).

The oldest cover rock stratigraphic unit in section C-C' is Blowhard Formation of Upper Kapitean (latest Miocene) age, which unconformably overlies basement. It crops out west of Glenross Fault, which is closely associated with Ruahine Fault. There are two main outliers. The more structurally complicated is the one east of Kuripapango and beneath Mount Kohinga. Within it, Mangatoro Formation (Upper Opoitian - Waipipian), which is age equivalent to parts of Pakaututu, Puketitiri and Titiokura formations, unconformably overlies Blowhard Formation (equivalent to Mokonui Sandstone), although this contact is rarely exposed. In turn, Te Waka Formation unconformably overlies Mangatoro Formation. The outlier to the east between Ruahine Fault and Glenross Fault (Enclosure 1, Section C-C') has a thin succession of Tongaporutuan or Lower Kapitean sediment between basement and Blowhard Formation, based on its occurrence in outcrop a kilometre north of the cross-section line (Bland and Kamp 2014, Enclosure 4, Map Sheet 3). East of Glenross Fault for 4 km Te Waka Formation rests unconformably on basement; the latest Miocene – mid-Pliocene succession present to the west was removed prior to accumulation of Te Waka Formation. Farther to the east along the section line and in the vicinity of Kaweka State Forest Park and Tutaekuri River up to Mohaka Fault, Puketitiri Formation (Waipipian, mid-Pliocene) 60 to 160 m thick (thickening to the south) underlies Te Waka Formation. East of Mohaka Fault, Te Waka Formation and younger units are progressively exposed towards the axis of the basin. There is little control on the subsurface stratigraphy and structure, which is drawn in the section line based on the outcrop pattern, with the maintenance of unit thicknesses. The vertical offset on Mohaka, Patoka, Waiwhare and related faults is comparatively minor and does not greatly affect the dip of basement to the east beneath the late Neogene succession. Although the decrease in dip upwards through the stratigraphy and into the axis of the basin is subtle, it does indicate concurrent tilting of the western basin margin concurrent with sedimentation, as described above for sections A-A' and B-B'(Enclosure 1).

Cross-section D-D'

Cross-section D-D' is oriented WSW-ENE through Ohara Depression, Wakarara Range and Kereru (Enclosure 1) (Bland and Kamp 2014, Enclosure 4, Map Sheets 5 and 6). It shows a different structural arrangement between the late Neogene succession and basement exposed in the west compared with the three cross-section records to the north (A-A', B-B', C-C'). Based on the composite logs for Kereru-1, Taradale-1 and Hukarere-1, the basin contains very thick occurrences of Puketitiri Formation and the lower part of Taradale Formation (Mangapanian, Late Pliocene) compared with equivalent units in the parts of the basin to the north. In addition, a fault (Wakarara Fault) sharply juxtaposes basement of the eastern margin of Wakarara Range against the late Neogene basin succession (Enclosure 1, Section D-D').

Ruahine Fault and Mohaka Fault bound the western and eastern margins of Ohara Depression, which contain an inlier of Puketitiri Formation, Sentry Box Formation and Esk Mudstone of Upper Mangapanian and Lower Nukumaruan age (Late Pliocene – Early Pleistocene). The disparate thicknesses of Puketitiri Formation in Ohara Depression versus east of Wakarara Range imply either a formerly steep easterly facing slope on the basement surface across basement now exposed in Wakarara Range, or a faulted margin during the Mangapanian, or a combination of both. That the Upper Nukumaruan Okauawa Formation immediately east of Wakarara Range is strongly folded as part of the Wakarara Monocline implies major reverse movement on Wakarara Fault during the Pleistocene. While this allows for Wakarara Fault to have existed during the Mangapanian, it may also suggest that a comparatively steep basement slope existed along the western margin of the basin in this area during the Late Pliocene. Thus prior topography existed across the Ruahine and possibly Wakarara ranges, with comparatively late onlap by marine facies (Upper Mangapanian and Lower Nukumaruan) prior to substantial reverse faulting that led to uplift of Ohara Depression and the adjacent ranges. The pattern in cross-sections A-A', B-B' and C-C' for basin-ward tilting and uplift of basement along the western margin concurrent with subsidence and sedimentation in the forearc basin axis is not so evident in the structural development in the most southerly section D-D'.

Synthesis of structure revealed in the cross-sections

Four cross-sections drawn across and oblique to the basin axis reveal the first order structure of the basin and give insights to its development. Section A-A' shows the least deformation. The shallowing of dip upwards through the succession indicates uplift of the western margin (leading to exposure of basement) concurrent with subsidence and sedimentation and a possible eastward shift in the location of the basin axis. Sections B-B' and C-C' show very similar overall structure to each other. Important elements are the (i) eastward dip of basement beneath the late Neogene succession, mildly interrupted by late reverse faulting (Mohaka Fault and related fault zone), and (ii), uplift (inversion) of the basin margin concurrent with sedimentation in the basin axis along with evidence for Mangapanian (c. 3 Ma) differential erosion and deposition within the western margin (Te Waka Formation unconformable over older units), followed by Pleistocene uplift and erosion of the late Neogene succession, leaving outliers of Late Miocene and Pliocene units in the west upon elevated basement. Section D-D', amongst all of the cross-sections, shows the greatest degree of structure development, amount of reverse faulting and basin inversion. In the geological maps that accompany the cross-sections (Bland and Kamp 2014, Enclosure 4) it is evident that in the south-western part of the basin (western part of section

D-D'), the axis of the basin is highly oblique to the strike of the main faults (Ruahine and Mohaka faults), an observation that is consistent with the greater degree of mapped structure development and basin inversion to be found there.

The broad patterns in the structure – (i) minimum Upper Opoitian–Pleistocene age of uplift of basement in the west (Kaweka and Ahimanawa ranges) concurrent with subsidence and sedimentation (offlap) in cross-sections A-A', B-B' and C-C'; and (ii), late (Late Pliocene; Mangapaian) marine onlap of basement of the Ruahine and Wakarara ranges coupled with late (Middle Pleistocene) marked reverse fault offset and basin inversion, points to complexity and different tectonic drivers along the northern versus southern parts of the western basin margin. The north-western parts of the margin (Kuripapango – Mohaka River) show evidence of basement tilting from at least the Upper Opoitian (late-Early Pliocene, c. 4.7 Ma), with later superimposed dextral oblique and dip-slip faulting within the Mohaka Fault Zone. The oblique-slip faulting (Ruahine and Mohaka and related faults) propagated northward, affecting the area during Late Pliocene sedimentation. Hence the basin-wide structure was affected primarily by uplift and tilting in the northwest, subsidence in the axis of the basin, and uplift in the southeast concurrent with sedimentation above a growing accretionary wedge. The faulting and uplift in the North Island Shear Belt along the western basin margin is a secondary and younger structural development with propagation of faults from south to north. By contrast, the parts of the map area in the southwest (Cross-section D-D'), which includes the northern parts of Ruahine Range and Wakarara Range, do not show evidence for concurrent uplift of basement and basin sedimentation from the Upper Opoitian. There was prior basement topography, late (Mangapanian) marine onlap of a steep margin, probably partly faulted, and this area has undergone more substantial faulting and basement uplift than the northwestern parts of the basin. Hence the forearc basin in central Hawke's Bay lies adjacent to two different basement structural-geomorphic domains, an older one (late-Early Pliocene) in the northwest (Kaweka and Ahimanawa ranges and others to the north) and a younger one (Middle Pleistocene) in the southwest (Ruahine and Wakarara ranges). Major reverse faults (Ruahine and Mohaka) now link the two domains, but these faults propagated to the north after the Late Pliocene (c. 3 Ma).

In the following sections we systematically describe each of the fault and fold structures in the map area drawing on our own and published information. This has value for hazard assessment whether that is in relation to infrastructure, safety in relation to seismic events, or for resource exploration purposes (e.g. seismic hazard assessment for hydrocarbon drilling). We undertake this description in the context of loosely defined structural domains. This is followed by interpretation and discussion of the timing of past faulting.

Description of structural domains, faults and folds

Axial Range Domain

The Axial Range Domain (Fig. 5) is characterised by oblique-slip faults, including the Wellington, Ruahine, Mohaka and Whakatane faults and related structures. These faults have active traces, extend for 400 - 500 km in a NNE direction (030°) (Beanland et al. 1998) (Fig. 3) and represent seismic hazard for the region.

The Ruahine Fault (Figs 6 & 7) and Mohaka Fault (Fig. 8) are the most significant faults in the map area in terms of lateral continuity and offset and along parts of them they mark a geological boundary at the surface between basement and Neogene cover strata (Figs 9 & 10). The vertical offset on these faults is probably less than the strike-slip displacement, although the cumulative amount of the horizontal component of offset is difficult to measure (Erdman and Kelsey 1992). For the Ruahine Fault the ratio of horizontal to vertical offset is estimated at 2.1:1 and for Mohaka Fault in the Ohara Depression it ranges between >1:1 to 8:1 (Erdman and Kelsey 1992).

The Axial Range Domain also contains numerous reverse (dip-slip) faults of varying throw. Kaweka Fault is located west of Ruahine Fault (Figs 4, 10) and the main structure bounding basement that underlies Kaweka Range. The trace of Kaweka Fault ends at the surface between the confluence of the Mohaka and Ripia rivers and the Napier-Taupo Road (SH5) (Fig. 4). The Kaweka and Glenross faults (Fig. 4) may converge at depth with the Ruahine and Mohaka faults.

Ruahine Fault

The generally straight trace of Ruahine Fault indicates that it has a steeply dipping fault plane (Browne, 1981; Beanland, 1995). Vertical dips have been reported for Ruahine Fault by Beanland (1995) in southern and central parts of the map area. In the Ohara Depression (Fig. 11) the fault plane strikes 032° and has vertical dip. Striae on the fault plane trend 32° and plunge 25° (Erdman and Kelsey 1992). In the Omahaki area and near the upper Tutaekuri River the fault plane dips 75°SE and Late Quaternary displacement is almost pure strike-slip (Beanland 1995). Offset on an early Holocene terrace riser across Ruahine Fault at Puketitiri indicates a slip rate of 0.7 - 1.5 mm/y (Beanland 1995). Although not considered reliable by Beanland (1995), it does provide an

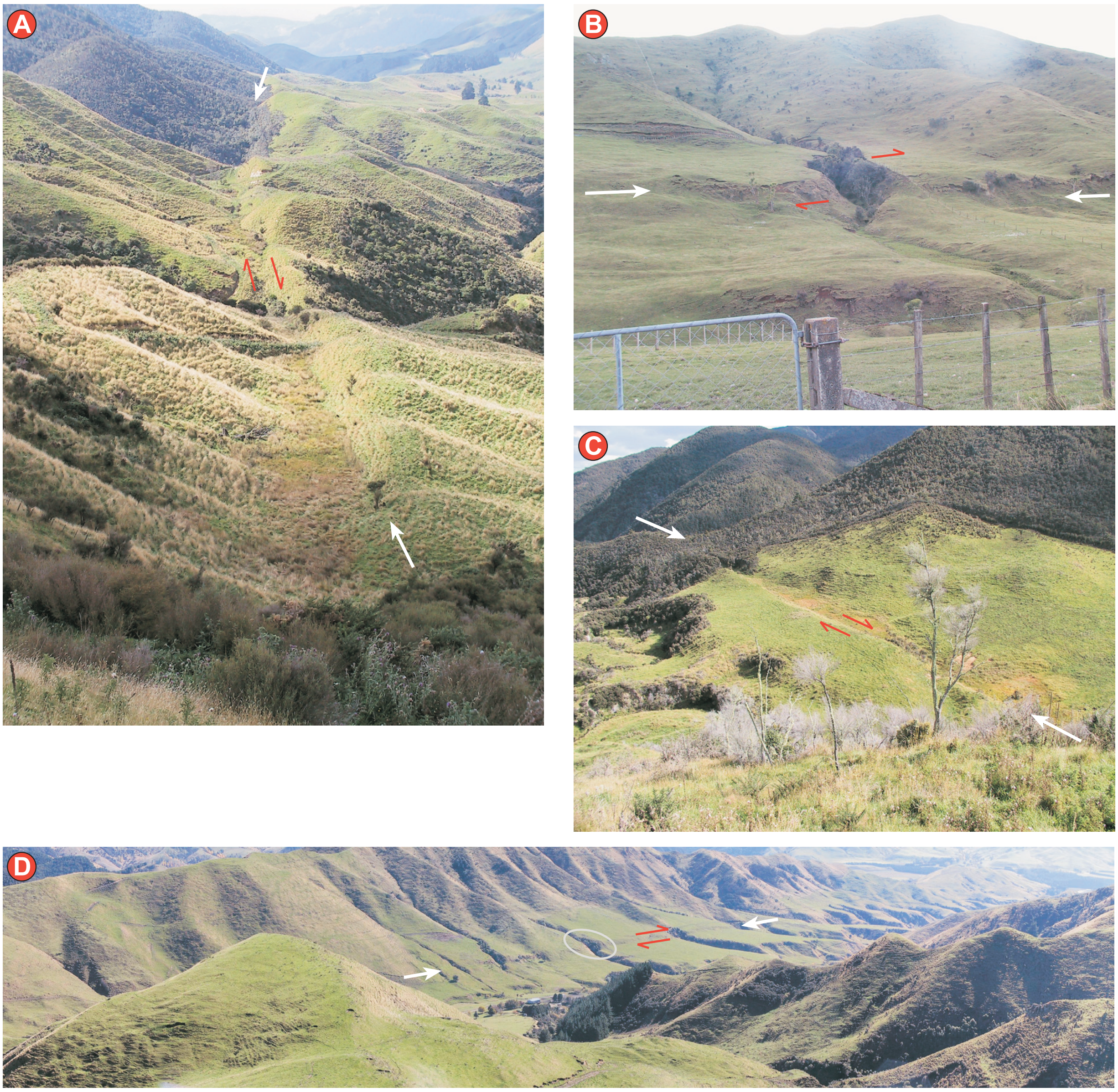


Fig. 6 : Photographs of active traces of Ruahine Fault (white arrows) in the Puketitiri area, western Hawke's Bay. Note how the expression of the fault changes along strike from a topographic furrow to a ridge. Range topography lies across or against the fault in images A and C, and are set back from the fault in B and D. Red arrows indicate direction of dextral offset. A) View northeast of Baldy Quarry, Whittle Road. Photo location: U20/090976. B) View west of Hot Springs Road at a right-lateral offset stream course highlighted by the white circle in image D. Photo location: V20/124144. C) View southwest from Lucknow Road, Kaweka Forest Park. Photo location: U20/085069. D) View of Ruahine Fault from Hukanui Station, looking northwest across Hot Springs Road. Photo location V20/120117.

order of magnitude for the slip rate on Ruahine Fault. There are no data to constrain the slip rate on Ruahine Fault in Ohara Depression. Beanland and Berryman (1987) estimated present day slip on the whole Ruahine Fault as 1 - 2 mm/y.

Dextrally offset stream courses across Ruahine Fault are prominent in the Puketitiri and Pakaututu areas (Fig. 6B). Recent displacement has resulted in upthrow on the western side of the fault, although geological cross-sections through this area suggest that since the Early Pliocene there has been substantial uplift of the eastern block of at least 300 m (Enclosure 1). This is indicated by the presence of Early Pliocene Pakaututu Formation on Torlesse basement around the Ruahine Fault in the Puketitiri and Pakaututu areas (Bland and Kamp 2014).

Vertical offset on Ruahine Fault in the Tutaekuri River area is likely to be several hundred metres. Estimates of offset are hampered by the lack of stratigraphic markers either side of the fault. Displacement on Ruahine Fault along Ohara Depression has resulted in substantial uplift of Torlesse basement forming Ruahine Range. An outlier of Sentry Box Formation preserved at Seconds Ridge on the northern end of the range indicates a minimum of 300 m of vertical offset since the base of the Nukumaruan (2.4. Ma). In terms of the cumulative amount of horizontal offset on Ruahine Fault, Beanland (1995) suggested 7-10 km since the Early Pliocene. Based on the proximity of distinctive Hukanui Limestone Member (Pakaututu Formation) either side of Ruahine Fault in the Puketitiri and Pakaututu areas, we concur with the estimate made by Beanland (1995).

The nature of the active trace of the Ruahine Fault changes character related to proximity of the Ruahine Range to the fault. North of Baldy Quarry (Fig. 7) a prominent series of sag ponds are visible, with upthrown ridges on the eastern side of what has previously been viewed as the modern fault trace (Fig. 6A, C). Where Ruahine Range is farther from the fault trace (e.g. Hot Springs Road), a prominent bench higher on the western side occurs, with stream courses offset across the fault marking dextral strike-slip displacement (Fig. 6B, D). Few sag ponds are present along this more northern part of the fault trace. These observations are similar to those reported by Eusden et al. (2005) for fault structures in North Canterbury along the Hope Fault and relate to interaction between fault displacement, topography and surface processes.

Glenross Fault

Glenross Fault (Fig. 4) was named and mapped in its central and northern parts by Browne (1981), the name being derived from the bounding Glenross Range. The surface trace of Glenross Fault separates from Ruahine Fault in the south near McIndoe Flat in the northern Ohara Depression and merges again north of Tutaekuri River. The Glenross Fault defines the eastern margin of Omahaki Depression, and, with the Ruahine Fault, bounds the Glenross Range.

While the fault plane has not been observed in outcrop, a wide zone of strongly sheared and shattered greywacke occurs where Glenross Fault crosses Lizard Road in Kaweka Forest (U20/038909). Strongly shattered greywacke and a series of prominent defects are also visible where the fault crosses Tutaekuri River downstream of the Lawrence Road swing-bridge (U20/ 063980). The inferred trace of Glenross Fault, which strikes about 020°, is usually well defined by a series of steeply northwest-dipping (30°- 65°) outcrops of Te Waka Formation. These outcrops lie adjacent to the fault from Awapai Station northeast to The Lizard. Some 1 - 2 km to the east of Glenross Fault, Te Waka Formation dips more gently at 15 - 25° to the southeast as part of Glenross Range.

Lizard Fault

Lizard Fault (Fig. 4) has a short trace that strikes about 027° and converges towards Glenross Fault around The Lizard, Kaweka Forest. It was first mapped and described by Browne (1981). The interaction between the Lizard and Glenross faults is responsible for the steeply dipping Te Waka Formation that forms The Lizard. To the east of Lizard Fault, Te Waka Formation dips at over 60° NW whereas to the west it dips at 25° SE. The dip decreases towards Lizard Fault.

Fig. 7: Ruahine Fault Zone exposed in the face of Baldy Quarry (excavating Mesozoic Torlesse basement) Kaweka Forest Park. The main trace of Ruahine Fault lies about 100 m east (left) of this outcrop. Photo location: U20/090076.

Comet Fault

Comet Fault (Fig. 4) was mapped by Kingma (1957). Browne (1986) inferred Comet Fault to have a near-vertical fault plane based on is straight trace. It lies several kilometres northwest of Ruahine Fault and truncates the northern end of Miroroa Fault. Approximately 9 km southwest of Mount Miroroa, Comet Fault downthrows to the NW by 200 m an erosion surface developed on Torlesse basement. (Browne 1986). Kingma (1957) qualitatively estimated 1 km of throw on Comet Fault but this can't be substantiated. Browne (1981) estimated 30 m of throw at The Blowhard. East of Burns Range the fault displaces Blowhard Formation to the east, opposite to the direction of throw at Comet Range and Mount Miroroa. The fault trace cannot be mapped north of Tutaekuri River (Browne 1986). There appear to be no markers of displacement on the fault.

Miroroa Thrust

Miroroa Thrust (Fig. 4) was first mapped by Kingma (1957) and was investigated in more detail by Browne (1981, 1986). Miroroa Thrust, as with adjacent Comet Fault, is an inactive structure. It is named after Mount Miroroa (Cattle Hill) south of the Napier-Taihape Road. The fault trends NW-SE (strike about 123°) and separates Torlesse basement from Lower (basal) Nukumaruan (Late Pliocene) sandstone, siltstone and limestone. Although surface outcrops indicate a fault plane dipping at 45°, the dip probably steepens at depth as its outcrop trace is linear along its 3 km length (Browne 1986). Miroroa Thrust links Ruahine Fault with Comet Fault located 3 km to the northwest, perhaps acting as a transfer structure. On the northern slopes of Mount Miroroa, Torlesse basement is separated from basal Nukumaruan rocks by a 2 - 5 cm-thick dark-grey gouge orientated 107/45° SE (Browne 1986). The overthrust Torlesse basement indicates displacement after Lower Nukumaruan.

Kaweka Fault

Kaweka Fault (Fig. 4) is a relatively short but significant structure in the North Island Shear Belt. It extends from Kuripapango to Pakaututu, diverges south-westward from Ruahine Fault, and may represent a transfer structure. Kaweka Fault bounds the east side of Kaweka Range with a very steep escarpment (Beanland 1995). Beanland (1995) measured a dip of 80° on the fault plane near Kuripapango and observed slickensides with shallow plunge (045/ 10°SE). This suggests that the fault may accommodate a significant component of strike-slip motion. Through the Kuripapango and Pakaututu areas the fault strikes 035° and is characterised by steep, triangular faceted spurs. Kaweka Fault rapidly diminishes in throw northward from Kuripapango and the trace cannot be identified north of Ripia River at Pakaututu. Measured vertical offset on Upper Opoitian limestone (Hukanui Limestone Member, Pakaututu Formation) on basement at the northern end of Kaweka Range is about 120 m (upthrow on west side of fault). This contrasts with the nearly 1000 m of west-side-up throw estimated at Kuripapango by Browne (1981, 2004). Browne's estimate seems anomalously high compared to that of other faults in the domain. It was based on inferred displacement of Torlesse basement underlying Late-Early Pliocene Mangatoro Formation, which Browne (1981, 2004) estimated as being up to 1500 m thick. Our more regional investigations suggest a thickness of less than 550 m is more likely and in the immediate Kuripapango area is probably only 200-300 m thick. This reduces the inferred throw on Kaweka Fault to several hundred metres. In the northern area near Makahu River triangular-faceted spurs are present, although not as well developed as those in the south. The western side of the fault is consistently upthrown. No data exist for modern slip rates on Kaweka Fault.

Mohaka Fault

Mohaka Fault (Fig. 4) is the eastern branch of Wellington Fault (Langridge et al. 2005) and is currently a dextral oblique-slip fault (Raub 1987; Beanland et al. 1998). It is taken here as the boundary between the Axial Range Domain and the Range Front Contractional Domain (Fig. 5). Geological mapping suggests that Mohaka Fault has several sections, each several kilometres long having similar strike. In southern and central parts of the map area the straight fault trace suggests that the fault plane has a near vertical dip (Beanland 1995). In northern parts of the map area the plane has a distinct dip to the northwest (Cutten 1994). The occurrence of discrete sections to the fault suggests that it has not yet become a through-going strike-slip fault (e.g. Wesnousky 1988).

Mohaka River to Napier-Taupo Road(SH5) section of Mohaka Fault

The Mohaka to SH5 section of Mohaka Fault contains several active traces, especially in the area around Waitara Road. Traces of the Mohaka Fault are arranged in a left-stepping pattern, separated by more northerly-striking segments (Cutten 1994; Beanland 1995), and uplift of the surface can occur on both western and eastern sides of the fault in different segments.

Hawkston Station to SH5 section of Mohaka Fault

Throw on the Hawkston Station to SH5 section of Mohaka Fault decreases from Te Waka Range to Hawkston Station, and is reflected in lowering of the summit ridge elevations of Te Waka and Maniaroa ranges. Uplift occurs on the eastern side of the fault. The Maniaroa Range (east of Mohaka Fault) is uplifted topography, with Te Waka Formation exposed on both sides of the fault. Kingma (1958a) reported no evidence of strike-slip displacement on Mohaka Fault through the Patoka-Puketitiri area, but estimated about "700 ft" (~210 m) of vertical displacement, which is in agreement with our observations. Active traces of the fault in this area are not obvious.

Greywacke basement is exposed immediately west of Mohaka Fault near Potter Road on Cherry Block Station, which contrasts with the inferred east-side-up displacement (as shown by the presence of the Maniaroa Range) described above. This suggests that while uplift has recently occurred on the eastern side of the fault, on a longer timescale uplift on the western side to expose basement has been more pronounced. Changes through time in sense of displacement are common on strike-slip faults.

Hawkeston Station to Big Hill section of Mohaka Fault

Mohaka Fault extends from Awapai Station in the southwest to Hawkston Station in the northeast. Vertical offset is greatest at the southwestern end of this segment along the eastern side of Big Hill and diminishes to the northeast. The western side is up thrown.

Around Big Hill, Torlesse basement is juxtaposed against Late Pliocene beds of Mangaheia Group (Fig. 8E) with at least several hundred metres of throw. The fault trace is well exposed on Hawkston Station (Fig. 8A, B) and where it passes through Whana Valley. On Hawkston Station the fault trace is marked by a series of steeply dipping, well cemented limestone ridges that parallel the fault trace and its associated sag ponds and offset streams. Prominent splays off the main fault trace are clearly evident on aerial photographs through the Whana Valley area.

Mohaka Fault is very well expressed in Ngaruroro River valley at Kohatunui Station where the river emerges from a deep greywacke gorge (Fig. 8E). Broken formation consisting of strongly shattered basement (upstream) and Lower Nukumaruan Esk Mudstone (downstream) occurs for approximately 120 m upstream and downstream, respectively, of the vertical fault plane of Mohaka Fault. Vertical displacement since Lower Nukumaruan (Late Pliocene) at this site is a minimum of 600 m upthrown to the west. This degree of throw diminishes rapidly north-eastward to Hawkston Station. Near Mangatutu Stream Bridge on Hawkston Road, displacement of Te Waka Formation is minimal. Northeast of this bridge the sense of displacement changes to east-side-up along the Maniaroa and Te Waka Ranges.

Big Hill to Ohara Depression section of Mohaka Fault

Mohaka Fault is a significant structural feature between Big Hill and Ohara Depression. There is some strike-slip displacement on Mohaka Fault. Most of the shortening in this area is expressed east of Wakarara Range (Erdman and Kelsey 1992). The base of the Neogene succession is exposed on Mount Mary, where greywacke-pebbly-rich facies of Mount Mary Pebbly Limestone overlies Torlesse basement (U21/969681). To the west of Mohaka Fault, Neogene rocks are commonly observed to onlap

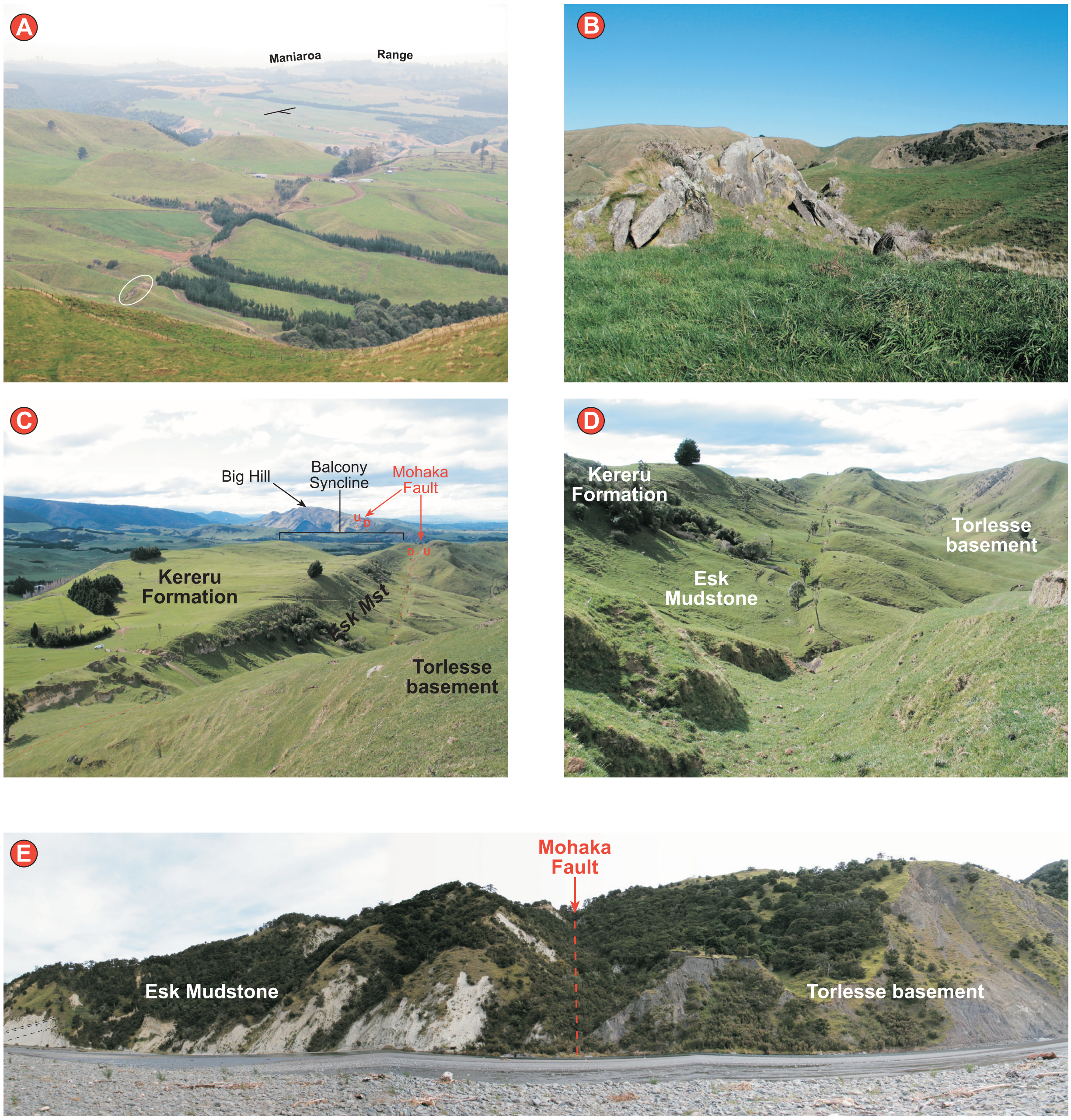


Fig. 8: Views of active traces of Mohaka Fault from the Ohara Depression to Puketitiri area. A) Fault trace viewed from Mangatutu Station looking north. The direction of dip on the top of Te Waka Formation on the western side of the fault is indicated. The white oval indicates the outcrop in the centre of image B. Photo taken from V20/134966. B) Strongly recrystallised limestone of probable Te Waka Formation cropping out immediately to the east of the active trace of Mohaka Fault on Hawkston Station. Nearby shutter ridges and offset streams indicate recent strike-slip displacement on this section of the fault. Photo location: V20/134979. C) Fault trace (highlighted in red dashed line) viewed from the slopes of Mount Mary, Glendale Farm, Ohara Depression. Late Pliocene Esk Mudstone and Kereru Formation are folded in the adjacent Balcony Syncline, constraining the post Lower Nukumaruan timing and magnitude of displacement of this part of the fault. Torlesse basement is juxtaposed against Late Pliocene sediments across the fault. Photo taken from U21/969681, looking northwest. D) View of an active trace of Mohaka Fault. Note the presence of shutter ridges and offset streams across the fault trace. Relative uplift is to the east (right) side of the fault. Photo location: U21/968682. E) Exposure of Mohaka Fault in Ngaruroro River valley, Whana Valley. Torlesse basement is juxtaposed against Late Pliocene Esk Mudstone, indicating displacement on the fault post-"middle" Nukumaruan. This exposure of the fault is less than 15 km from the exposures in images C and D. Photo location: U21/022770.

basement. The fault plane at the surface in this area strikes 029° and dips 89° ± 5° SE (Beanland 1995). South of Ohara Depression, Raub (1985) and Raub et al. (1987) reported dips on Mohaka Fault at four sites ranging between 84°NW to 90°. Slickensides on the fault plane trend 032° and 030° and plunge 25° and 47° (Erdman and Kelsey 1992). The sense of motion from these data is dextral with a minor southeast-side-up component (Beanland 1995). Two estimates of slip rate by Raub (1985) were made on this part of Mohaka Fault at the southern end of the Ohara Depression. From terrace riser and channel offsets cut into aggradational terraces, he determined slip rates of 3.0 ± 0.7 and 3.1 ± 0.5 mm/y for the past 35 and 11 k.y., respectively.

Mohaka Fault trace is well exposed on Glendale Farm in the Ohara Depression, where it strikes 030° and marks the western face of Wakarara Range (Fig. 8C, D). Kaweka Terrane crops out on the western side of the fault and Pahau Terrane on the east (Lee etal. 2011) (occasionally overlain by Mount Mary Pebbly Limestone). Kereru Formation and Esk Mudstone crop out on the western side of Mohaka Fault. From Glendale Farm to Mangleton Road the active trace of Mohaka Fault is well expressed with a prominent series of sag ponds, swampy intervals and shutter ridges.

Big Hill Fault strikes off Mohaka Fault at the southern end of Big Hill and acts to transfer strike-slip motion from Mohaka to Ruahine Fault (Erdman and Kelsey 1992). North of Big Hill Fault, strike-slip displacement seems to have been more significant on Ruahine Fault compared with Mohaka Fault.

Fault displacement on Mohaka Fault

Average Late Quaternary slip on Mohaka Fault in the south of the map area is estimated at about 3 - 7 mm/y (Raub et al. 1987). It is difficult to determine the total horizontal offset on Mohaka Fault, as there are few, if any, appropriate markers. North of Ohara Depression Ruahine Fault appears to be the dominant strike-slip fault. South of this point Mohaka Fault may be the dominant strike-slip feature. Offset streams and shutters ridges are common along Mohaka Fault in the Ohara Depression, and are rare north of Hawkston Station. As shown above, the sense of vertical offset on Mohaka Fault varies throughout the study area. The lack of appropriate marker horizons across Mohaka Fault hinders determination of the total amount of dextral-slip on this fault, which may be of the order of a few hundred metres. Most of the displacement probably occurred during the past 0.5 m.y.

Vertical displacement on Mohaka Fault since the Early Pliocene varies along the strike of the fault. From the northern part of the map area to Hawkston Station, vertical offset appears to be around 100-200 m. Uplift is on the western side of the fault. Through this area displacement is shown by offset on Te Waka Formation, and expressed topographically as Maniaroa Range. Near Hawkston Station there is no vertical offset of this formation. South of Hawkston Station the amount of vertical displacement across the fault steadily increases and by the Ngaruroro River and Big Hill, displacement is at least several hundred metres, with uplift on the western side of the fault. South of Big Hill in the Ohara Depression vertical offset is also at least several hundred metres from topographic constraints, there being no marker horizons to measure offsets precisely. Uplift in this southern area is to the east (Wakarara Range).

North of Hawkston Station the active trace of Mohaka Fault becomes less well defined. This may reflect displacement being preferentially taken up on Ruahine Fault, or other faults to the east (Patoka Fault Zone and Rangiora Fault). A series of reverse and strike-slip faults splinter off Mohaka Fault from left-stepping jogs in its trace near Corbin Road (Waiwhare and Waihau Faults), the Tutaekuri River (Patoka Fault Zone) and at Puketitiri Road (Te Waka Range Splinter Fault). These faults are described in more detail below as part of the Range Front Contractional Domain. Rangiora Fault is inferred to splinter off Mohaka Fault in the area of the southern Maungaharuru Range.

Big Hill Fault

Big Hill Fault (Fig. 4) was named by Erdman and Kelsey (1992), the name being derived

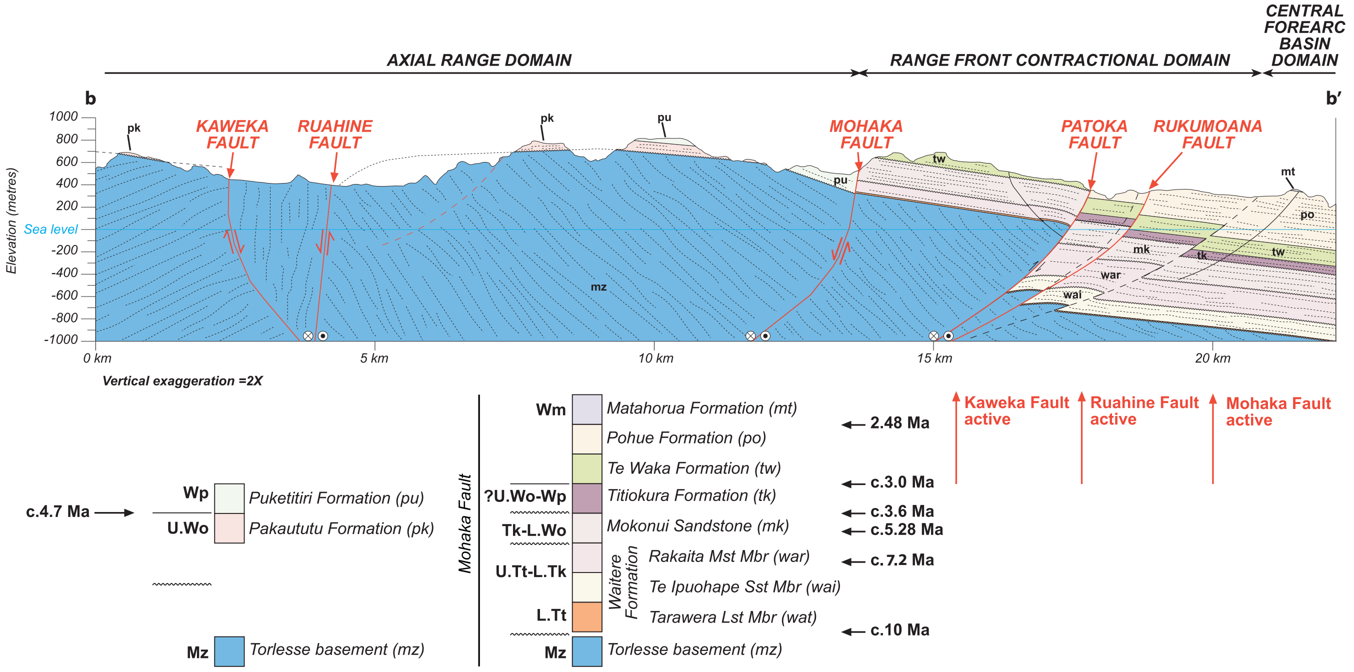


Fig. 9: Northwest - southeast geological cross-section across the axial range and range front contractional domains in the Pakaututu area (line b-b' in Fig. 5; western part of line B-B' in Enclosure 1). There is a change in stratigraphy across the Mohaka and Patoka Faults.

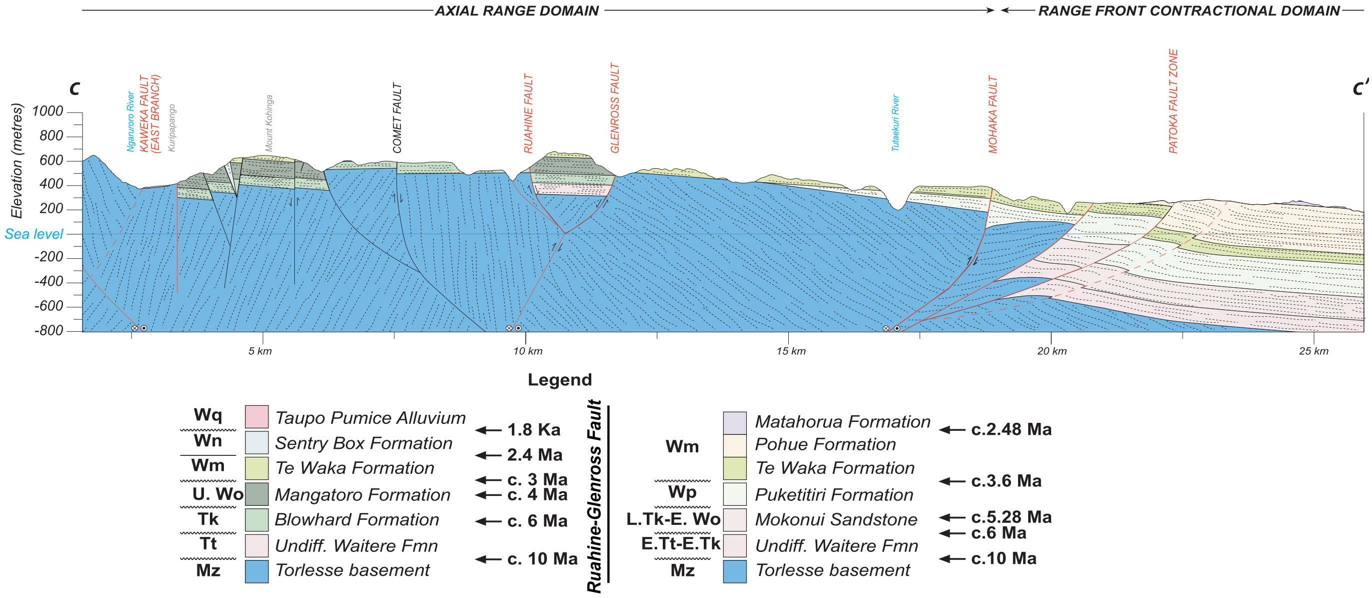


Fig. 10: West - East geological cross-section across the axial range and range front contractional domains in the Kuripapango area (line c-c' in Fig. 5; western part of line C-C' in Enclosure 1). Note the change in stratigraphy across Ruahine Fault, and the presence of Te Waka Formation across much of the area.

from Big Hill, a prominent greywacke block at the northern end of Ohara Depression. The southern end of Big Hill Fault strikes south-southeast and is a reverse fault upon which the Big Hill block has been uplifted (Bland and Kamp 2014, Enclosure 4, Map Sheet 5 Kereru). North to Ngaruroro River the fault strikes more northerly and the sense of displacement changes to mainly strike-slip (Erdman and Kelsey 1992). Big Hill Fault transfers motion from Mohaka Fault to Ruahine Fault within the northern part of Ohara Depression.

Thorn Flat Fault

Thorn Flat Fault is a reverse fault with an active trace in Ohara Depression near Rocky Outcrop (Fig. 11). It strikes between 005° and 070° with an arcuate surface trace. There are no constraints on slip rates. Erdman and Kelsey (1992) inferred west-northwest shortening across Ohara Depression by the transfer of strike-slip motion from Mohaka Fault to Ruahine Fault on Big Hill Fault, and they inferred this transfer as the mechanism behind the formation of Thorn Flat Fault and adjacent Herricks Anticline and Herricks Syncline (see below). They suggested that Thorn Flat Fault formed and propagated to the surface after initial formation of Herricks Anticline and Herricks Syncline.

Herricks Anticline

Herricks Anticline is located in Ohara Depression between Ruahine and Mohaka faults near the southern end of Big Hill Fault (Fig. 12). Herricks Anticline is associated with domed basement uplift (Beanland 1995) and lies immediately east of the surface trace of Thorn Flat Fault, an active reverse fault (Erdman and Kelsey 1992). Greywacke lies less than 100 m below the ground surface at Herricks Anticline, determined from the presence of strong reflectors in a seismic line (Beanland 1995). The anticline is cored by basement and involves overlying Puketitiri Formation. Surface expression of the anticline is defined by Sentry Box Formation, which dips moderately to steeply on both limbs of the fold (up to 55° on the western limb and 21° on the eastern limb; Kelsey et al. 1993). The fold axis trends 175°. East of Herricks Anticline beds dip southeast toward Mohaka Fault. West of the anticline Herricks Syncline deforms beds.

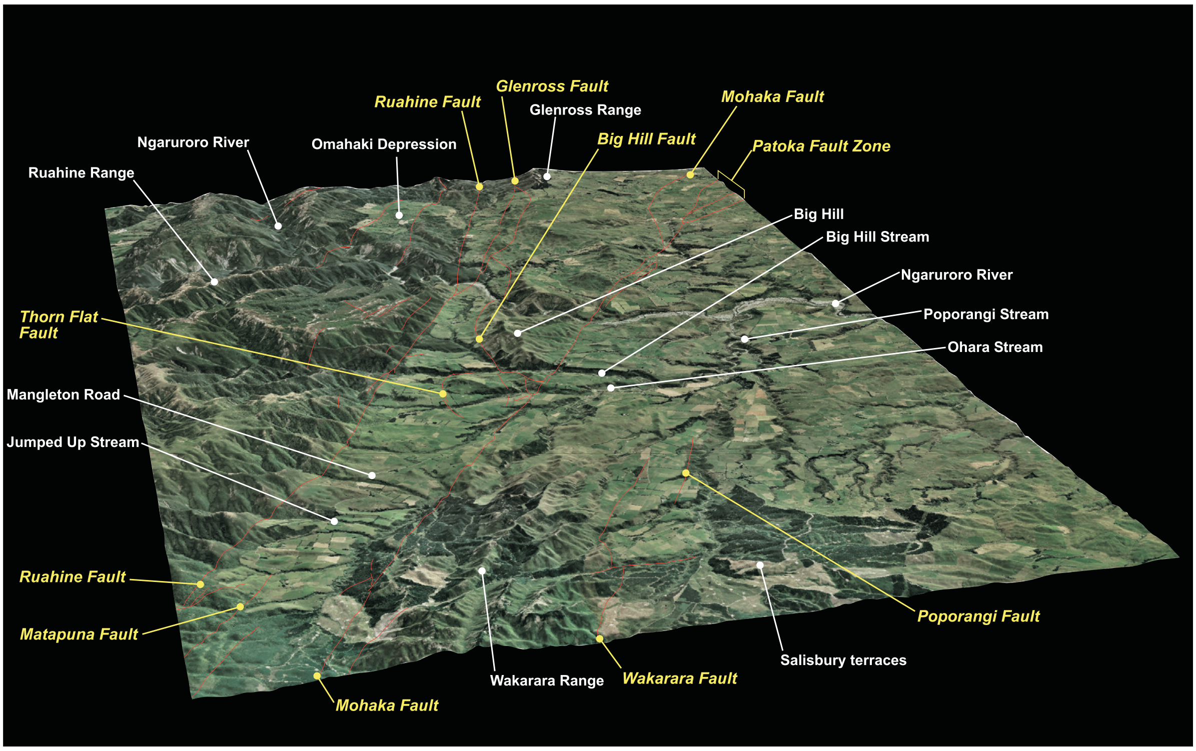


Fig. 11: Oblique reconstructed aerial view from the south of Ohara Depression and Kereru district illustrating the occurrence of faults and topographic features of the area. Active faults are shown with red lines. Note the way the Ruahine and Mohaka Faults define the Ohara Depression. Aerial photos used in this figure are derived from the LINZ NZMS260 U21 orthophoto database. Elevation is derived from the LINZ NZMS260 digital topographic dataset.

Herricks Syncline

Herricks Syncline (Fig. 12) lies west of Herricks Anticline and 1 - 1.5 km east of Ruahine Fault. The fold is cored by Esk Mudstone. The fold axis trends about 019°. Ruahine Fault truncates its western limb with basement juxtaposed against Esk Mudstone.

Balcony Syncline

Balcony Syncline (Fig. 8C, 12) occurs on the western face of Wakarara Range below Mount Mary and is bound along its eastern margin by a well-developed active trace of Mohaka Fault. It is cored by Esk Mudstone and Kereru Formation and is a prominent topographic feature. Limbs on the syncline dip 30-35° and the fold axis trends 030° nearly parallel to the strike of Mohaka Fault. Southwest of Balcony Syncline similar deformation occurs along the western edge of Mohaka Fault in Kereru Formation. The formation of Balcony Syncline relates to re-activation of the Ohara Depression sector of Mohaka Fault after the Upper Nukumaruan.

Kohinga Syncline

Kohinga Syncline (Fig. 12) is a prominent feature forming the summit of Mount Kohinga above Kuripapango. It is a strongly faulted feature. The northwest limb of Kohinga Syncline dips 55° SE and the southeast limb dips at 24° NW (Browne 1981). The axis of the syncline plunges towards the northeast. The northwest limb of the syncline is commonly displaced by normal faults with throws of up to 40 m. Te Waka Formation cores the fold.

Range front contractional domain

Range-front structures mostly comprise reverse faults with associated monoclines (e.g. Wakarara Monocline, Fig. 12) and anticlines in a zone located west of Mohaka Fault (Fig. 5). Some strike-slip faulting is evident in the domain. The principal faults are the Wakarara, Patoka, Rukumoana and Rangiora faults. In the south of the study area (Kereru district) the domain is on average 5 km wide, increasing to 13 km wide in the north of the map area (Maungaharuru Range). This increase in width reflects the widening of the forearc basin north of the latitude of Napier. The topography in this domain is strongly controlled by structural features as shown in Fig. 13. Range Front Domain structures commonly form the boundary between Torlesse basement and Neogene sedimentary rocks of the forearc basin, but this domain also extends into the forearc basin fill succession. East of this domain Mesozoic basement is down-faulted to significant depths (Fig. 9, 10, Enclosure 1).

Wakarara Fault

Wakarara Fault (Fig. 4, 13, 15) is a reverse fault. The fault displaces Torlesse basement by at least 1100 m and it bounds Wakarara Range. There are no Late Quaternary traces along the fault and Beanland (1995) reported no observed dextral offsets. Uncommon Holocene traces mapped in the Wakarara area by Raub (1985) are probably associated with cross faults and bedding-parallel faults (Beanland 1995). The location of the fault is marked by a series of steeply dipping to near vertical ridges of Kereru Formation that crop out along the eastern side of Wakarara Range (Fig. 13, 15). Erdman and Kelsey (1992) measured the Wakarara Fault plane as having a dip of 60-80° W. Erdman and Kelsey (1992) reported striations at several locations as being consistent with reverse displacement with a small amount of dextral slip.

The fault loses its surface expression north of Wakarara Range near the axis of a monoclinal fold named Wakarara Monocline (Erdman and Kelsey 1992) (Fig. 12). Wakarara Fault parallels and locally overthrusts the axis of Wakarara Monocline along the eastern front of Wakarara Range.

Te Kowhai Fault

Identification of Te Kowhai Fault (Fig. 4) in this study is based in part from a trace mapped by Grindley (1960). It is probably mainly a blind reverse fault that passes from Mangatutu Station to the northern edge of Te Kowhai Station where basement is up to the west by about 100 m relative to Te Waka Formation. On Mangatutu Station, Te Waka Formation is folded adjacent to the inferred location of the fault.

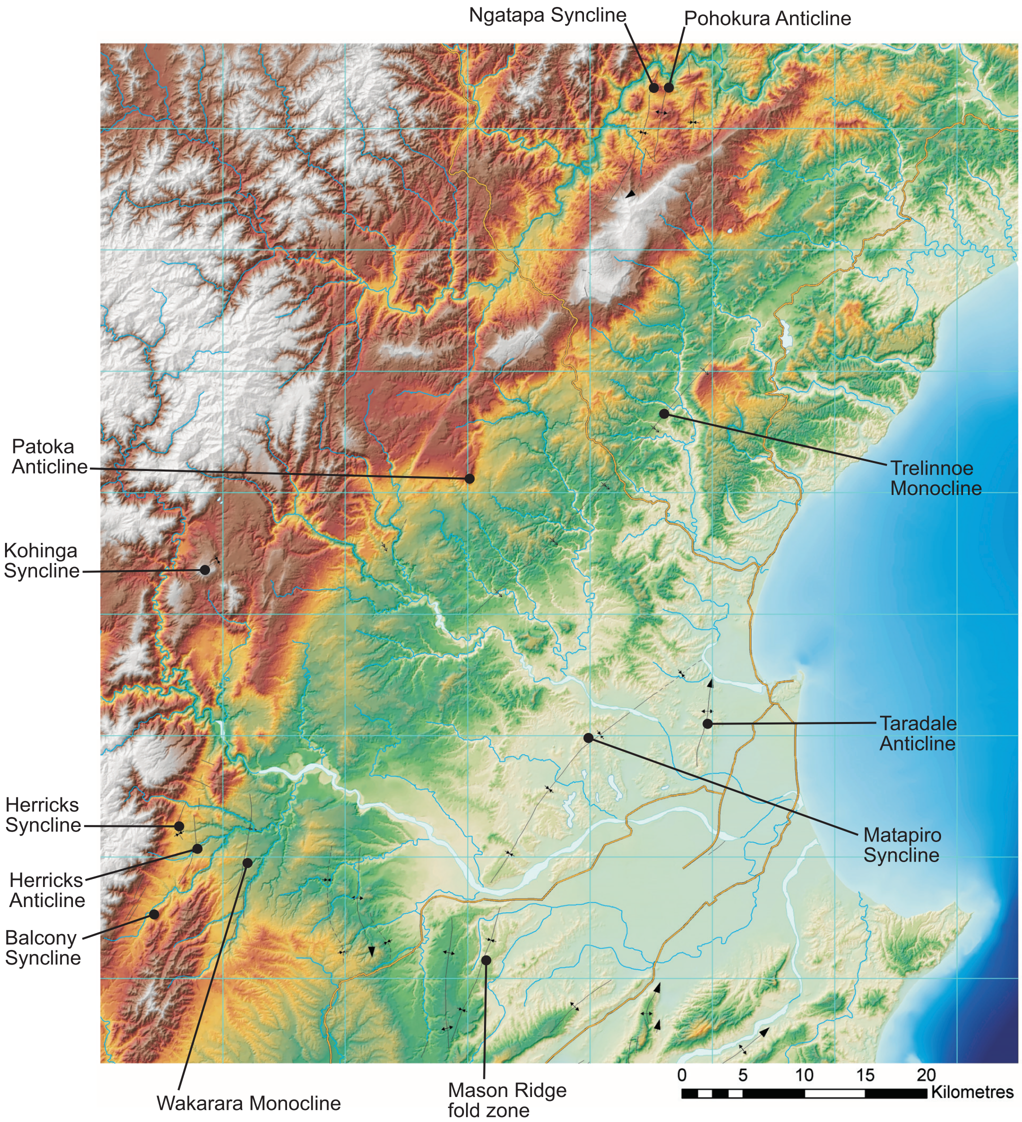


Fig. 12: Occurrence of folds in the central Hawke's Bay map area.

Patoka Fault Zone

Patoka Fault Zone diverges from Mohaka Fault (Figs 9, 10) and extends NE–SW from Hawkston Station to Te Pohue and consists of a series of reverse and dextral oblique-slip faults that trend NE-SW (Fig. 4). Patoka Fault Zone comprises Patoka Fault (Fig. 14) and Rukumoana Fault and several other prominent fault traces and lineaments. Kingma (1958b) estimated up to "400 ft" (~120 m) vertical offset on Patoka Fault about 3.2 km north of Patoka Village and commented that there was no evidence of strike-slip displacement on this fault. However, spurs and streams show dextral offset of up to 13 m at Potaka (Halliday et al. 2003)(Fig. 14). At least three displacements during the past 5,300 years have been identified from trenching and description of the fault trace at Patoka Village (Fig. 14). Halliday et al. (2003) suggested that Patoka Fault developed during the Holocene, but this is not consistent with the geology surrounding the fault. Halliday et al. (2003) inferred a maximum vertical slip-rate on Patoka Fault of 0.21 mm/y. Rob Langridge (in Litchfield et al. 2005) estimated the maximum dextral slip-rate on the fault as 1.9 - 3.2 mm/y, similar to that estimated for Mohaka Fault in its section to the south. It is possible that strike-slip displacement on Patoka Fault takes up the displacement observed on Mohaka Fault south of the point where these faults diverge (Figs 4, 13). No basement is known at the surface east of Patoka Fault.

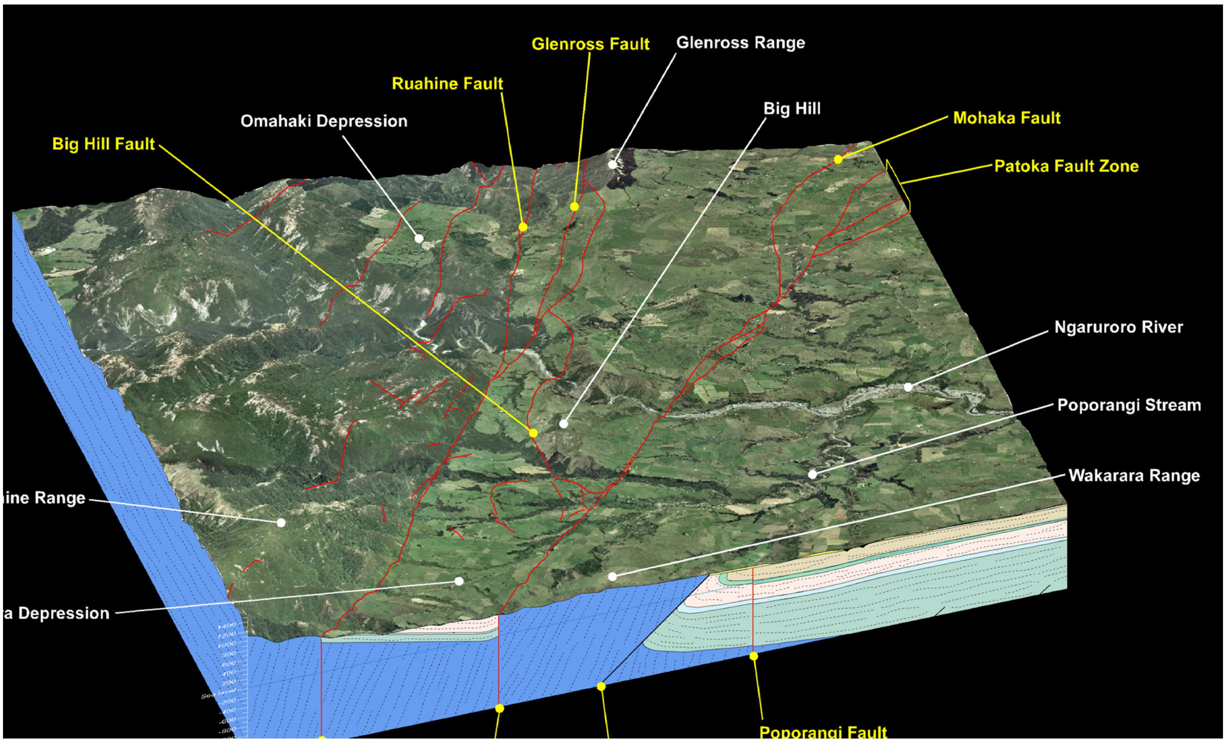


Fig. 13: Oblique aerial view of northern end of Ohara Depression to Glenross Range. The southern cross-section is from Fig. 5 (line d-d') and 14 projected from the south. View is from the southwest and the distance across the lower edge of the image is approximately 20 km. Note the thickness of Neogene sedimentary section east of Wakarara Range compared with that in the Ohara Depression between the Ruahine and Wakahara ranges. Aerial photographs derived from LINZ NZMS 260 U21 orthophoto database. For geological unit colours refer to Fig. 10. Elevation is derived from the LINZ NZMS260 digital topographic dataset.

Waiwhare Fault

Waiwhare Fault was shown on Grindley's 1960 map and active traces are recorded in the GNS Science active faults database. It lies within the Patoka Fault Zone and it marks the eastern edge of Te Waka Formation at Waiwhare (Fig. 4). The fault strikes from Lee Road across the Napier-Taihape Road, River Road and Mangatutu Road and the trace is inferred to end at Mangatutu Stream (Fig. 4). It is upthrown on its western side.

Waihau Fault

Waihau Fault lies within the Patoka Fault Zone and is inferred from discontinuous active traces, deformation of Neogene strata and lineaments evident on digital elevation models and air photographs (Fig. 4). The fault marks the western margin of Matahorua Formation from Puketitiri Road through Waihau Road to the Waiwhare area. Matahorua Formation is downthrown on the eastern side of fault. Total throw on the fault is uncertain, but is probably of the order of <100 m.

Rukumoana Fault

Rukumoana Fault strikes NE-SW along the base of Te Waka Range to Te Pohue (Fig. 4). It was mapped by Stonely et al. (1958), Francis (1991), Bland (2001) and Leith (2003). Rukumoana Fault is the northernmost part of Patoka Fault Zone, which is a 21 km-long series of active fault traces (Fig. 4).

Rukumoana Fault is marked by a monocline in Te Waka Formation at Te Pohue where no fault plane has been identified and hence it is mainly a northwest dipping blind reverse fault (Bland 2001). It is imaged on seismic reflection profiles to steepen at depth (Wylie 1993). Dextral strike-slip displacement has been inferred (e.g. Begg et al. 1994), although there is little supportive field evidence. Vertical offset at depth is estimated from our mapping to be a minimum of 60-100 m (Bland 2001). Possible active fault traces have been observed north of Te Pohue (Rob Langridge, GNS Science, pers. comm. 2005). Deep-seated landslide scars and landslide debris that could result from formation of a monocline in the Neogene strata obscure the surface in this area.

Te Waka Range Splinter Fault

Te Waka Range Splinter Fault (Fig. 4) strikes NE-SW along the crest of Te Waka Range to the west of the microwave tower. It is a relatively minor structure that lies between Mohaka and Rukumoana Faults. Neall et al. (1995) mapped 15 km of strike-length as an extensional splinter trace of Mohaka Fault. In its southern section the fault has an orientation of 034/85° W and can be traced to below Te Waka Trig where it splays and appears to terminate (Leith 2003). The fault is normal and may express surficial gravitational collapse of Neogene strata in the western face of Te Waka Range. At Te Waka Trig the western side of the fault has 30 m of vertical offset. Total displacement is likely to increase towards the southwest within the main part of the trace where it could be 60-100 m. Displacement has been identified as both pre- and post- the 11 850 y B.P. Waiohau Tephra (Neall et al. 1995). Offset on this fault may be associated with a large landslide in the central Maniaroa Range in the headwaters of Waipunga Stream.

Rangiora Fault

The Rangiora Fault (Fig. 4) is a 14 km-long structure located about 40 km north of Napier and 13 km east of Mohaka Fault. A 5 km-long Late Quaternary trace occurs along the central section of this fault at Rangiora Station near Waikare River (Cutten et al. 1988). The fault was mapped by Grindley (1960), Cutten (1994) and Graafhuis (2001). The fault strikes 030°, oblique to the strike (055°) of Mangaheia Group. The linear trace of the fault over hill country and changes in the sense of vertical offset along the fault suggest that the fault plane has steep dip (Cutten et al. 1988). Total vertical offset on the fault is unknown, but is likely to be less than a few 10s of metres (Cutten et al. 1988; Graafhuis 2001). At the northern end of the fault trace at Waikare River, Cutten (1994) reported a series of river terraces to be dextrally offset with progressive displacements of 5 - 15 m. Cutten et al. (1988) inferred three events each involving 4 - 6 m right lateral displacement, with one event occurring between 3,300 and 1,900 years ago and two during the last 1,900 years. Rangiora Fault is inferred to have had an average late Holocene slip rate of 4.5 mm/y (Cutten et al. 1998), comparable to that of Mohaka and Ruahine faults.

Wakarara Monocline

Wakarara Monocline has developed as a consequence of reverse offset on Wakarara Fault (see above) (Erdman and Kelsey 1992) (Figs 14, 16). This monocline strikes 035° for about 30 km along the eastern side of Wakarara Range. North of the range the trend becomes more westerly (190°). It is locally overturned along the eastern Wakarara Range front and terminates north of Ohara Stream. This is marked by steeply dipping ridges of Kereru Formation, examples occurring near Poporangi Road. Raub (1985) described southern parts of Wakarara Monocline. Wakarara Monocline is well exposed at the confluence of Ohara Stream and Big Hill Stream where beds of Kereru and Okauawa formations dip steeply in cliff faces (Fig. 16). Along the eastern face of Wakarara Range Kereru Formation has vertical dips.

Patoka Anticline

Patoka Anticline was first described and named by Kingma (1958b) and is geomorphically expressed in Patoka Hill. This structure has developed in Te Waka Formation immediately adjacent to Patoka Fault and probably formed as a fault-propagation fold (Bland and Kamp 2014, Enclosure 4, Map Sheet 3). The southern limb dips at about 13°SW and the northern limb dips up to 20°E. South of the anticline towards Price Cockburn Road, dip on Te Waka Formation steadily becomes more easterly, and by Mangatutu Station Te Waka Formation dips 9° SE, more consistent with the regional dip to the southeast.

Pohokura Anticline

Pohokura Anticline (Fig. 12) is an asymmetric fold whose fold axis was mapped by Cutten (1994). It was previously named the Dam Site Anticline in Cutten (1988). The fold deforms Early Miocene strata in the area around Waitere Station in the northern part of the map area. The hinge of the fold is well exposed in Anticline Creek at V19/405322 where beds in the eastern limb have strike and dip of 205°/68°E; and beds on the western limb are 156°/49°W (Cutten 1994).

Fig. 14: Photographs of the active trace of Patoka Fault on Raumati Station (V20/199997). Uplift is on the northwest side of the fault. Note sag ponds in images B and C. This part of Patoka Fault trace was trenched by Halliday (2003) and Halliday et al. (2003).

Central forearc basin domain

The Central Forearc Basin Domain is an area of relatively subdued topography where the underlying sedimentary succession has very shallow dips of a few degrees (Figs 5, 15). Deformation is minor with NNE-trending reverse faults and folds and associated anticlines, which broadly parallel the basin trend (Fig. 12). Northwest of Hastings and Napier the sedimentary succession forms the Hawke's Bay Monocline and dips decrease from about 20° to 2° between Mohaka Valley and Heretaunga Plains (Enclosure 1, sections A-A', B-B', C-C'). Matapiro Syncline marks the centre of the forearc basin.

Glengarry Fault

Glengarry Fault (030°) displaces Matahorua Formation through Glengarry Forest and across the Napier-Taupo State Highway from Patoka to Trelinnoe Station (Fig. 4). Its exact trace is mostly inferred, although outcrop patterns of Late Pliocene sedimentary rocks in the area strongly support its presence (Bland and Kamp 2014). No active traces have been observed. The surface position of the fault aligns it with a subsurface Eastern Patoka Fault inferred from seismic reflection profiles by Leith (2003). At Trelinnoe Station vertical displacement on Glengarry Fault is less than 15 m with down-throw on the northwest side. Displacement increases to the southwest towards the Napier-Taupo Road and Glengarry Forest where it is about 80 m, diminishing thereafter to Waihau Road.

Ngaruroro River Fault

Ngaruroro River Fault is inferred to lie along the south bank of Ngaruroro River near the small settlement of Maraekakaho and Roys Hill (Fig. 4). It separates Lower Nukumaruan Mason Ridge Formation on the south side of the river (Mason Ridge block) from Upper Nukumaruan Petane and Kaiwaka formations on the north side of the river (Matapiro Block). Kingma (1971) mapped its trace and it seems to control the course of the Ngaruroro River in this area.

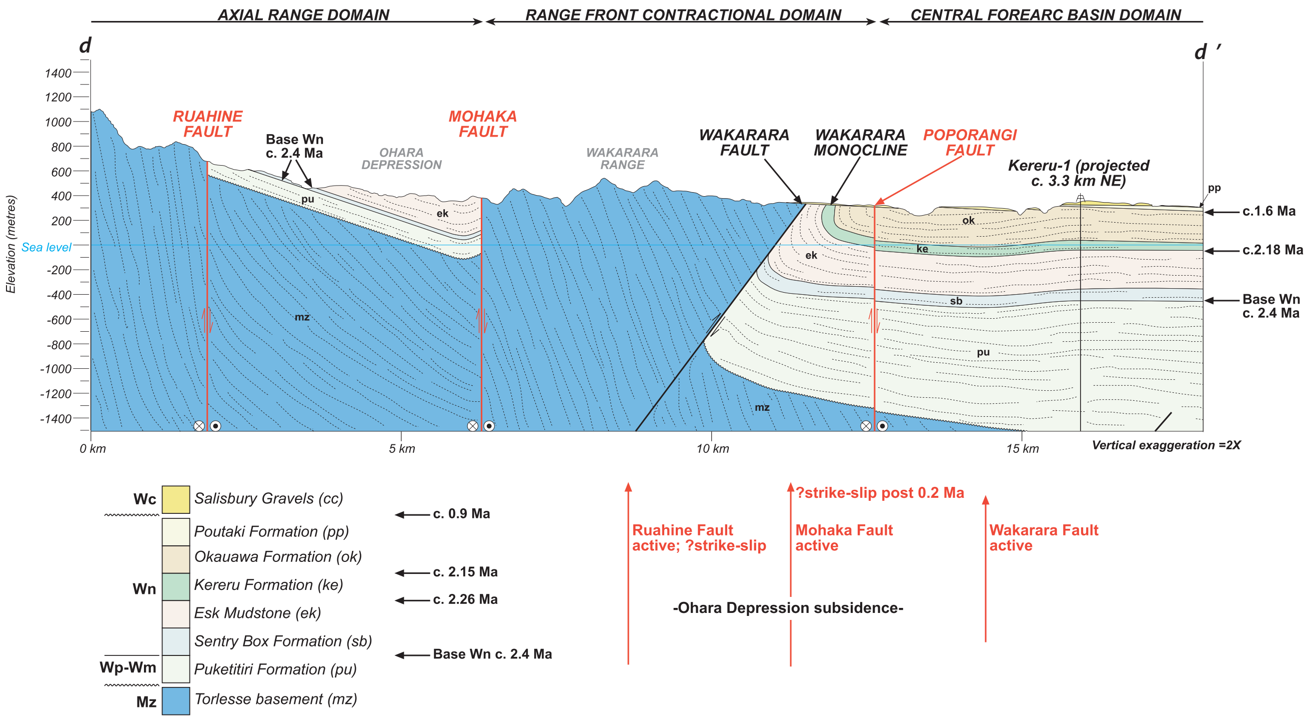


Fig. 15: Geological cross-section (line d-d' in Fig. 5), western part of line D-D' on Enclosure 1 from Ruahine Range to Kereru.

Another (unnamed) fault is inferred to separate the isolated Roys Hill block from the Mason Ridge and Matapiro blocks. Roys Hill is formed from "middle" Nukumaruan Park Island Limestone Member, which is not known from either the adjacent Matapiro or Mason Ridge blocks. Park Island Limestone Member probably underlies the Matapiro block, but has been eroded from the Mason Ridge block if it was ever deposited there.

The structural position of Fern Hill is also uncertain. Fern Hill lies on the south bank of Ngaruroro River adjacent to Omahu. Fern Hill is formed from Park Island Limestone Member, although it is faced immediately across the river by prominent bluffs of younger Waipatiki Limestone Member, suggesting that a fault separates the two areas.

Subsurface faults

Growing anticlines within the central forearc basin domain probably lie above reverse faults. Because of the non-indurated nature of the upper parts of the basin fill and minimal amounts of displacement, faults have failed to propagate to the ground surface. Hence the displacement at depth is expressed as force folds in upper stratigraphic units (Begg et al. 1994). The 1931 Napier earthquake, as an example, appears not to have resulted in significant surface rupture on a fault but was associated with surface displacement that may have been expressed as folding above a blind fault (Hull 1990; Begg et al. 1994).

Eastern Patoka Fault

The Eastern Patoka Fault was identified and named by Leith (2003), inferred from a strong, gently dipping reflector at about 2s TWT (Two Way Travel time) in seismic line EC91-4. This structure correlates well with a similar reflector at the western end of line WEC97-2 that occurs immediately below a broad ~5 km-wide anticlinal structure in the profile. The zone above the terminus of the fault consists of many small faults, each with vertical displacement of less than 20 m. The combined effect of numerous faults is "warping" of the surface above the inferred termination of the Eastern Patoka Fault (Leith 2003). The warping of the land surface can be observed from river long-profiles. The patterns suggest that the fault is active, as streams across it have not been able to cut down to grade.

Trelinnoe Fault

Trelinnoe Fault is a subsurface structure inferred from observations of seismic lines by Leith (2003), who incorrectly associated it with

Fig. 16: Surface expression of Wakarara Monocline in Ohara Stream at U21/026720. The monocline is a surface response to the blind Wakarara Fault. Ticked filled circles in the photograph indicate the changes in dip of Okauawa Formation across the monocline.

Wakarara Fault. It has been renamed Trelinnoe Fault to avoid confusion. The projected surface location of the fault is marked by a monocline named here Trelinnoe Monocline (Fig. 12). Seismic lines across this structure show little of the complex faulting observed above the adjacent Eastern Patoka Fault and overlying sedimentary rocks appear to have been deformed in a more ductile manner. To the east of the monocline upper parts of the sedimentary succession appear to be deformed by reverse faults induced by shortening of the sediments in the tightening fold hinge (Leith 2003). These faults are well defined on seismic line WEC97-1, dip to the west and are spaced approximately 200 m apart. They appear to terminate sharply at depth on a horizon interpreted to be the top of Grassy Knoll Conglomerate Member (Matahorua Formation).

Matapiro Syncline

Matapiro Syncline is the major structural feature affecting the outcrop pattern of Nukumaruan rocks through central portions of the map area (Fig. 12). Previously, the syncline was mapped from Ngaruroro River through the Puketapu area to the Esk River mouth (e.g. Grindley 1960; Kingma 1971; Beu 1995). Our geological mapping at 1: 50 000 suggests that Matapiro Syncline is not as extensive as previously inferred and extends from Ngaruroro River to Puketapu. Dips on beds in the syncline are typically 4°-2°. Development of the syncline occurred syndepositionally, as evidenced by dip-changes between older and younger units. Lithological differences occur between units exposed on either limb of the syncline, reflecting a depositional gradient across a paleoshelf. Matapiro Syncline terminates abruptly at Ngaruroro River channel near Roys Hill and does not continue south into the Mason Ridge area. North of Puketapu the western limb of Matapiro Syncline is referred to as Hawke's Bay Monocline.

Trelinnoe Monocline

Trelinnoe Monocline is the surface expression of Trelinnoe Fault, which lies at depth (Fig. 12). The dip of Late Pliocene sedimentary units increase from 8° to 15° across the monocline. The axis of the monocline is also marked by a series of landslides mapped by Leith (2003), which include the prominent Eland, Northlands and Deep Stream landslide complexes (Bland and Kamp 2014, Enclosure 4, Map Sheet 4).

Mason Ridge fold zone

The Mason Ridge area is characterised by a series of anticlines and synclines (Fig. 12) probably resulting from displacement on blind reverse faults. These anticlines were expressed as antiformal ridges upon which carbonate banks accumulated as Mason Ridge Formation.

Other folds

The folds underlying Mason Ridge (Fig. 12) are part of a belt of anticlines and synclines that extend from the northern Wakarara Range east to Raukawa Range (e.g. Fig. 3 in Cashman et al. 1992). Mapping by Kelsey et al. (1993) illustrates that many of the folds in this area are underlain by reverse faults at depth. This zone of folding corresponds to the area where the forearc basin narrows south of Hastings, perhaps indicating increasing contraction of the basin. This is probably due to encroachment of the accretionary wedge into the forearc basin fill. In the area around Rautoitoi Stream near Eskdale, Tutira Member beds show evidence for blind faulting, driving the formation of a surface fold.

Eastern contractional domain

The Eastern Contractional Domain (Fig. 4) comprises Raukawa Range east to the Maraetotara Plateau and offshore in the southeast part of the map area. It marks a zone of marked reverse faulting and related folding (Pettinga 1982). This domain includes the onland inboard part of the accretionary wedge. A similar style of deformation offshore underlies Hawke Bay (Barnes et al. 2002). Although the western margin of the domain is slightly diffuse, dense faulting marks it including Longlands, Poukawa (Kelsey et al. 1998), and Tukituki faults (Fig. 4). Structures in this domain accommodate principally contractional deformation (Cashman et al. 1992; Beanland 1995; Beanland et al. 1998).

Strata in coastal parts of this domain (Maraetotara Plateau, Cape Kidnappers area) are offset by a network of normal faults that have vertical displacements of up to many tens of metres (Kingma 1971; Cashman and Kelsey 1990; Cashman et al. 1992). Fault traces in this area (Maraetotara Fault Zone) (Fig. 4) are discontinuous and the zone varies in width from several hundred metres to about 8 km (Begg et al. 1994). Normal faults bound both east- and west-dipping fault blocks. Fault-slip indicators show nearly pure dip-slip displacement (Cashman et al. 1992). The relationship between the normal faults in the domain and the major reverse faults of the accretionary wedge at depth is poorly known, as is the depth to which the faults extend (Begg et al. 1994). The relationships between normal faults and deeper reverse faults is however better understood in offshore areas (e.g. Barnes and Nicol 2002; Barnes et al. 2002). Both Pettinga (1982) and Cashman et al. (1992) suggested that normal faults in this domain are a surface response to uplift and arching through contraction of the underlying accretionary wedge and are not representative of deformation at deeper levels. This was supported by Pettinga (2004) in a study of the character of large-scale gravitational collapse of the Maraetotara Plateau. In the Cape Kidnappers area Middle Pleistocene non- to marginal-marine sediments have been uplifted 125 m above sea level and are offset by normal faults with displacements of up to 9 m. Cashman et al. (1992) suggested that normal faulting in the Cape Kidnappers area began during the Late Pleistocene and continues to the present day.

Several recent hydrocarbon exploration wells (e.g. Whakatu-1, Hukarere-1; Fig. 5) have targeted anticline structures in the eastern contractional domain (Fig.17). Hawke Bay-1 targeted an anticline structure offshore the Port of Napier.

Napier Fault

Napier Fault is a NE-SW striking subsurface structure identified in seismic reflection profiles beneath Te Awa and Taradale and offshore from the Port of Napier (Hull 1990; Begg et al. 1994) (Figs 4, 17). The fault lies west of Scinde Island, its location constrained by seismic data acquired and processed as part of the Hukarere-1 exploration programme (Westech Energy New Zealand Ltd, 2001). Napier Fault is inferred to be reverse in nature (Begg et al. 1994). This fault and the associated anticline may have a history that goes back to the Lower Nukumaruan, creating seafloor relief (swell) upon which carbonate accumulated to form Scinde Island Formation. Napier Fault was inferred by Begg et al. (1994) to be the subsurface continuation of Poukawa Fault Zone, but a significant step-over would be required for this to be the case. It appears as though Begg et al. (1994) have confused the Napier Fault with the Awanui Fault, which lies farther east (see below).

Awanui Fault

Awanui Fault (Figs 4, 17) is inferred to extend from Bridge Pa beneath Flaxmere to the coast at Awatoto. Awanui Fault may be the northern part of Poukawa Fault (Hull 1990). The line of zero elevation change of the land surface around Napier/Hastings as a result of the 1931 earthquake, extending from Bridge Pa to Awatoto, may mark the surface projection of Awanui Fault (Henderson 1933; Haines and Darby 1987; Hull 1990).

Maraetotara Fault Zone

Strata in the Maraetotara Plateau and Cape Kidnappers areas are offset by a discontinuous network of 1-7 km-long normal faults that have vertical displacements up to many tens of metres (Cashman and Kelsey 1990; Cashman et al. 1992) (Fig. 4). In the Cape Kidnappers area, Late Pleistocene non- to marginal-marine sediments have been uplifted to over 125 m above sea level, tilted to the southwest and offset by normal faults with displacement of up to 9 m.

Poukawa Fault Zone

The Poukawa Fault Zone (Fig. 4) consists of a highly segmented series of 15 anatomising and en-echelon right and left-stepping dextral strike-slip, thrust and normal faults (Kelsey et al. 1993, 1998). Active folding accompanies faulting in this zone and fold axes often parallel the trends of associated faults (Cashman et al. 1992). Companion hanging wall anticlines are present in association with faults in the zone (Kelsey et al. 1998). The geomorphically expressed length of the fault zone is 34 km, although on the basis of co-seismic deformation associated with the 1931 Napier earthquake and the presence of blind faults north of the zone, the seismogenic length of the fault zone may be a much longer (Kelsey et al. 1998). The subsurface Awanui Fault may be a northeastern continuation of Poukawa Fault Zone.

The northernmost part of Poukawa Fault Zone occurs in southern parts of the map area between the Kaokaoroa and Raukawa ranges. Poukawa and Otane basins and two fault-bounded antiforms (Waikareao and Glenforsa anticlines) constitute the main structural elements of the wider fault zone (Cashman et al. 1992) and are south of the map area. Faults in the Poukawa Fault Zone typically strike NNE - SSW and dip 45-75° NW (Beanland et al. 1998). Cashman et al. (1992) inferred a Quaternary strike-slip displacement rate of 7-9 mm/y for the Poukawa Fault Zone, although this was not accepted by Beanland (1995). The fault zone is inferred to be developing to the east and north beneath Heretaunga Plains (Kelsey et al. 1998).

Tukituki Fault Zone

The Tukituki Fault Zone (Fig. 4) lies several kilometres east of the Poukawa Fault Zone, and occurs in southernmost parts of the map area. It comprises a series of NW-dipping reverse faults that strike NNE to SSW.

Taradale Anticline

On his geological map of the Matapiro-Napier area, Kingma (1971) showed an anticline in the hills immediately west of Taradale. Geological mapping as part of our work confirms the presence of this feature (Fig. 12). Park Island Limestone Member, which near Puketapu follows Puketitiri Road uphill towards Taradale, before dipping steeply down to Park Island reserve, defines the anticline. The Taradale Anticline is a north to northeast-plunging anticline that forms the eastern limb of Matapiro Syncline. It is inferred to be cored by a reverse fault. Beds dip up to 7° on the western limb and 1°- 4° on the eastern limb. It is probably related to a structure at depth targeted by the hydrocarbon exploration hole Taradale-1 (Figs 5, 17).

Napier Syncline

Napier Syncline (Figs 12, 17) location was documented by Hull (1990). The limbs of the syncline are erosionally truncated by Quaternary deposits (e.g. Middle Castlecliffian Kidnappers Group and Recent alluvium). It is bound on its western side by Awanui Fault. The anticline associated with its eastern limb was targeted as a hydrocarbon prospect in Whakatu-1 (Fig. 17). Napier Syncline may be a continuation of the unnamed syncline mapped by Beanland et al. (1998) to the east of Pakipaki ridge and Longlands Fault.

Lineaments

Lineaments have been defined from analysis of air photos and DEMs and are depicted on the geological maps in Bland and Kamp (2014, Enclosure 4). Most lineaments observed have the same structural grain as faults and folds in the map area. They display variable trace length. Features have been mapped as lineaments when they cannot be confirmed in the field as having discrete offset of beds.

Timing of structure development

In this section we are focussed on the timing of structure development, particularly of the faults within the North Island Shear Belt (NISB) along the western margin of the basin. There are two main sets of information: (i) a new set of 1:50 000 geological maps published by Bland and Kamp (2014, Enclosure 4) together with the stratigraphy of the succession within and adjacent to the fault zone (Bland et al. 2007; Kamp et al., 2007); and (ii), lithofacies patterns within the late Neogene succession that might be able to be related to the timing of uplift and erosion of basement along the western basin margin.

In interpretation of structure development from the stratigraphy of map units in and around the NISB, we place no value on the basal facies arising from the onlap of the late Neogene succession on to basement. Greywacke conglomerate occurs locally at the base of the Kapitean (Latest Miocene) Blowhard Formation and at the base of the Upper Opoitian (Early Pliocene) Pakaututu Formation (Bland et al. 2007; Bland and Kamp 2014). They accumulated in local depressions and hollows and arose from sedimentary processes in high energy non marine to near shore shelf environments; their distribution cannot be related to fault offset. These facies haveno significance in terms of development of the NISB as it (NISB) is younger than the Late Miocene and Early Pliocene succession it offsets.

Evidence from geological maps and stratigraphy

The geological maps (Sheets 1, 3 and 4) are rich in information about the dip-slip component of displacement on faults within the NISB, particularly the juxtaposition of stratigraphic units of different age, but there is little in the

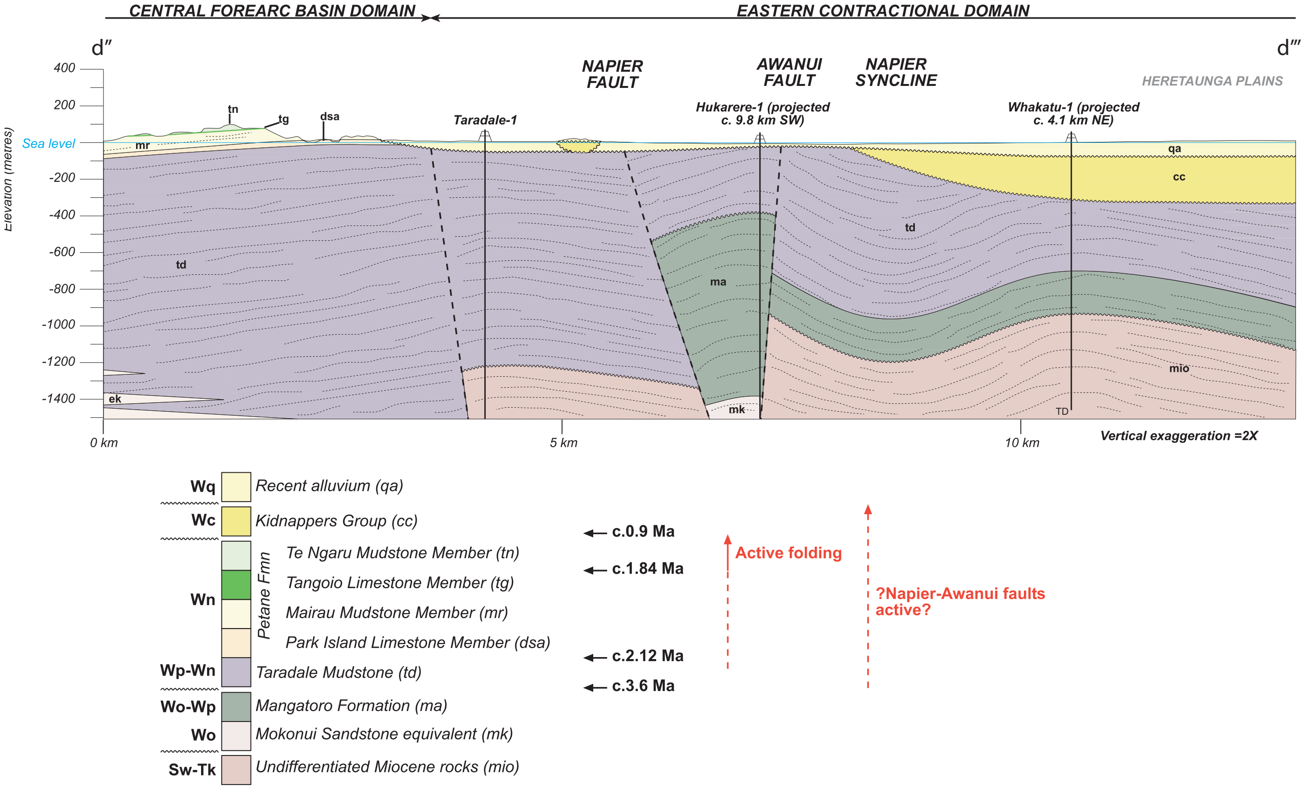


Fig. 17: Geological cross-section (line d”-d”’ in Fig. 5; eastern part of D-D’ in Enclosure 1) through the Taradale-Napier area. Also evident are the anticline structures targeted in Taradale-1, Hukarere-1 and Whakatu-1.

outcrop patterns of the units that can constrain the total amount of horizontal offset. Ruahine Fault is a continuous and comparatively straight fault through the map area and it has accommodated sufficient displacement for it to be a through-going strike-slip fault, which probably requires several kilometres of horizontal offset. By comparison, Mohaka Fault is comprised of multiple strands north of State Highway 5 and is probably not yet, at least in the north of the map area, a through-going strike-slip fault.

An unconformity is developed between Waitere Formation (Tongaporutuan – Lower Kapitean, c. 9.0 - 7.2 Ma) and Pakaututu Formation (Upper Opoitian, base c. 4.7 Ma) in outliers north and west of Mohaka River (Sheet 1). West of Kaweka Fault (Roston Station) Pakaututu Formation rests upon basement. The amount of Waitere Formation eroded at this unconformity is difficult to estimate and probably minor as the beds either side of the unconformity have similar dip and the area is near the southern limit of onlap of Waitere Formation; while Pakaututu Formation has overstepped Waitere Formation onto basement, the limit of Waitere Formation deposition (i.e. the highstand shoreline) may have been located in this area. There is little in the outcrop pattern to indicate existence of Ruahine Fault before or during accumulation of Pakaututu Formation. The unconformity marks a relative change in sea level that may have been associated with a eustatic lowstand followed by later onlap forming Pakaututu Formation.

A significant unconformity lies between Te Waka Formation and a range of underlying units. Between Ruahine and Glenross faults a Tongaporutuan to Upper Opoitian succession is unconformably overlain by Mangapanian Te Waka Formation, which oversteps to the south onto basement at Sandy Ridge (Map Sheet 3). Between Ruahine/Glenross faults and Mohaka Fault, Te Waka Formation overlies either basement or Puketitiri Formation. East of Mohaka Fault, Te Waka Formation either conformably overlies Waipipian Titiokura Formation/Pohue Formation or unconformably overlies Kapitean, or Lower Opoitian Mokonui Sandstone with marked erosional relief. This unconformity as a whole indicates some uplift along the basin margin coupled with erosion, which we infer to mark the start of Late Cenozoic movement on Ruahine and Mohaka faults within the lower part of the Mangapanian Stage, no older than 3.0 Ma. The subsequent widespread accumulation of Te Waka Formation in the area between these faults and to the east of Mohaka Fault suggests another phase of basin margin subsidence and sedimentation with minimal fault displacement.

Stratigraphic data within Ohara Depression also helps constrain the timing of displacement on Ruahine and Mohaka faults. Puketitiri Formation some 360 m thick of Mangapanian age (3.0 – 2.4 Ma) is the lowermost unit above basement in Ohara Depression (Bland and Kamp 2014). Puketitiri Formation in the southern part of the map area (Sheet 5) accumulated during the same stage (Mangapanian) as Te Waka Formation (Bland and Kamp 2014); the units comprise different facies, the former being wholly terrigenous and the latter having carbonate beds within a cyclothemic mixed carbonate-terrigenous succession. Putetitiri Formation in Ohara Depression is overlain by Lower Nukumaruan Sentry Box Formation (c. 2.4 Ma) some 10 m thick and then by about 380 m of (Lower Nukumaruan) Esk Mudstone.

Prior to accumulation of inner- to mid-shelf Puketitiri Formation, basement must have been exposed between the present day location of Ruahine and Wakarara ranges. We infer the start of accumulation of Puketitiri Formation as marking the start of displacement on Ruahine and Mohaka faults, as fault offset formed the depression. The age of Puketitiri Formation in this area, as for Te Waka Formation (above), can only be constrained to the Mangapanian Stage (3.0 – 2.4 Ma), although our sense is that lowermost Puketitiri Formation in the depression is younger than the base of the Mangapanian Stage because of the large disparity in thickness of Putetitiri Formation between the depression and the main part of the forearc basin east of Wakarara Range (Fig. 15; Enclosure 1, D-D'). Hence the (intra-) Mangapanian timing of initiation of offset on Ruahine and Mohaka faults in central Hawke's Bay is very similar in Ohara Depression to that of the area to the north (Napier-Taihape

Road). Because there is about 400 m of Lower Nukumaruan sedimentary section preserved in Ohara Depression, we infer about 0.5 - 1 m.y. duration of offset relative to sea level on Ruahine and Mohaka faults in this area. Subsequently, continuing crustal shortening resulted in the depression and its sedimentary succession being uplifted above sea level and partially eroded, while substantial topography developed over Ruahine and Wakarara ranges.

Evidence of age of faults from the age and distribution of conglomerate facies

Conglomerate beds are a distinctive facies within Mangaheia Group and Kidnappers Group. Figure 18 illustrates for a series of representative stratigraphic columns the occurrence and distribution of conglomerate beds of Late Pliocene (Upper Mangapanian) and Pleistocene (Nukumaruan and Castlecliffian) age in the map area. Enclosure 2 shows the same information as a panel for many more sections, their extent being shown on a geological map. There are three stratigraphic phases of accumulation of conglomerate and associated sandstone facies and they constrain the minimum age of emergence and erosion of basement along the western margin of the basin.

Pohue and Matahorua Formations

Pohue and Matahoura formations crop out within the northern part of the map area in central Hawke's Bay (Bland and Kamp 2014). They comprise four stratigraphic members (mapping units) including sandstone, conglomerate and mudstone facies. To enable accurate mapping of the four members, their base was taken as the base of prominent conglomerate units, which stand out in the landscape (Fig. 18), forming boundaries that can easily be traced on air photos and in the field. From a sequence stratigraphic perspective the way the facies have been assembled into mapping units (members) is not ideal, as the conglomerate beds (fluvial facies) have been disassociated in the stratigraphic nomenclature from the underlying sandstone (inner shelf facies) with which they have a gradational boundary; that is, the member (map unit) boundaries do not coincide with the sequence boundaries, which lie at the top of the conglomerate beds.

Pohue Formation is the lowermost unit of interest here, comprising mudstone (correlative of Taradale Mudstone) and thick sandstone between Puketitiri in the south and Waikare River in the north (Enclosure 2). Deep Stream Member has conglomerate at its base, which extends from Puketitiri Road to Waikoau River. It is overlain by mudstone (south) or sandstone facies (north). Trelinnoe Member shows a similar facies pattern, but the conglomerate and sandstone facies are more extensive to the south and north, and the thickest accumulation of sandstone occurs to the south (Te Pohue – Esk River) of that for Deep Stream Member (Enclosure 2). Papakiri Member has a similar extent of conglomerate facies (as Trelinnoe Member) but it is overlain by mudstone rather than sandstone. The Mangapanian – Nukumaruan boundary (2.4 Ma) lies at the top of this conglomerate (green line in Enclosure 2). The Grassy Knoll Conglomerate Member has been mapped solely as a conglomerate. It shows more extensive distribution to the south (Flag Range-Sherenden) but has less extent to the north than the conglomerate in Trelinnoe Member (Enclosure 2). Note the occurrence of conglomerate beds within Puketitiri Formation in Ohara Depression of Mangapanian age, equivalent to those within Matahoura Formation, although they are much more limited in extent (Fig. 18). We interpret the stratigraphic occurrence of greywacke conglomerate facies in Matahorua and Puketitiri formations as indicating contemporary uplift and erosion of greywacke basement during the latest Mangapanian and Lower Nukumaruan stages (c. 2.52 – 2.36 Ma) to the west of the forearc basin, and we develop this interpretation further in the text below.

Petane and Okauawa Formations

Conglomerate and associated sandstone units also occur with Petane and Okauawa formations (c. 1.94 – 1.7 Ma) (Fig. 18; Enclosure 2). In particular, conglomerate facies are mapped as Kikowhero - Tutira, Whakamarumaru – Darkys Spur (Tararere Conglomerate Bed) and Flag Range Conglomerate members, and as conglomerate beds within Kaiwaka Formation (Enclosure 2). This second phase of accumulation of conglomerate units occurs along the western margin of the basin and more extensively to the south (to Kereru) than in the underlying

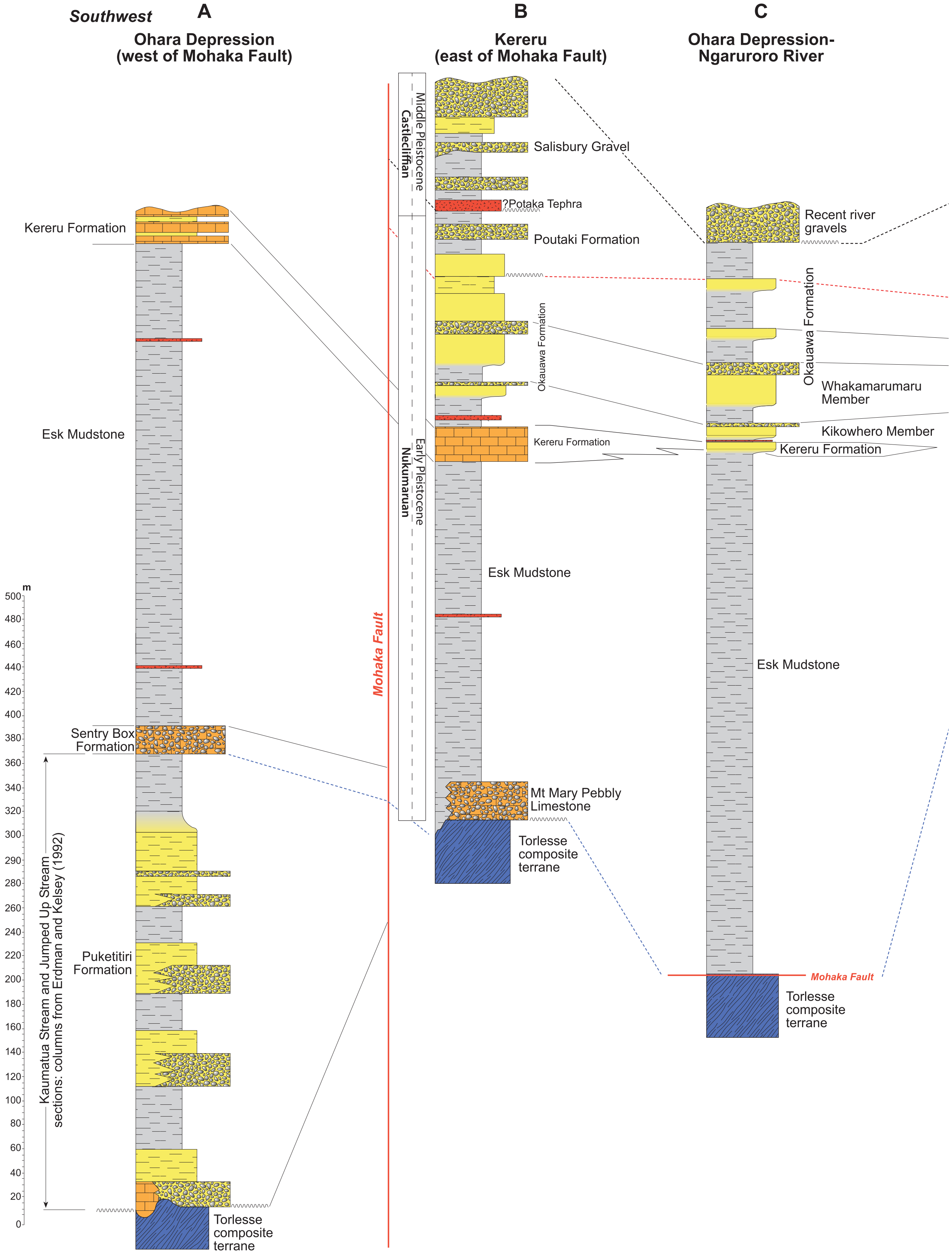
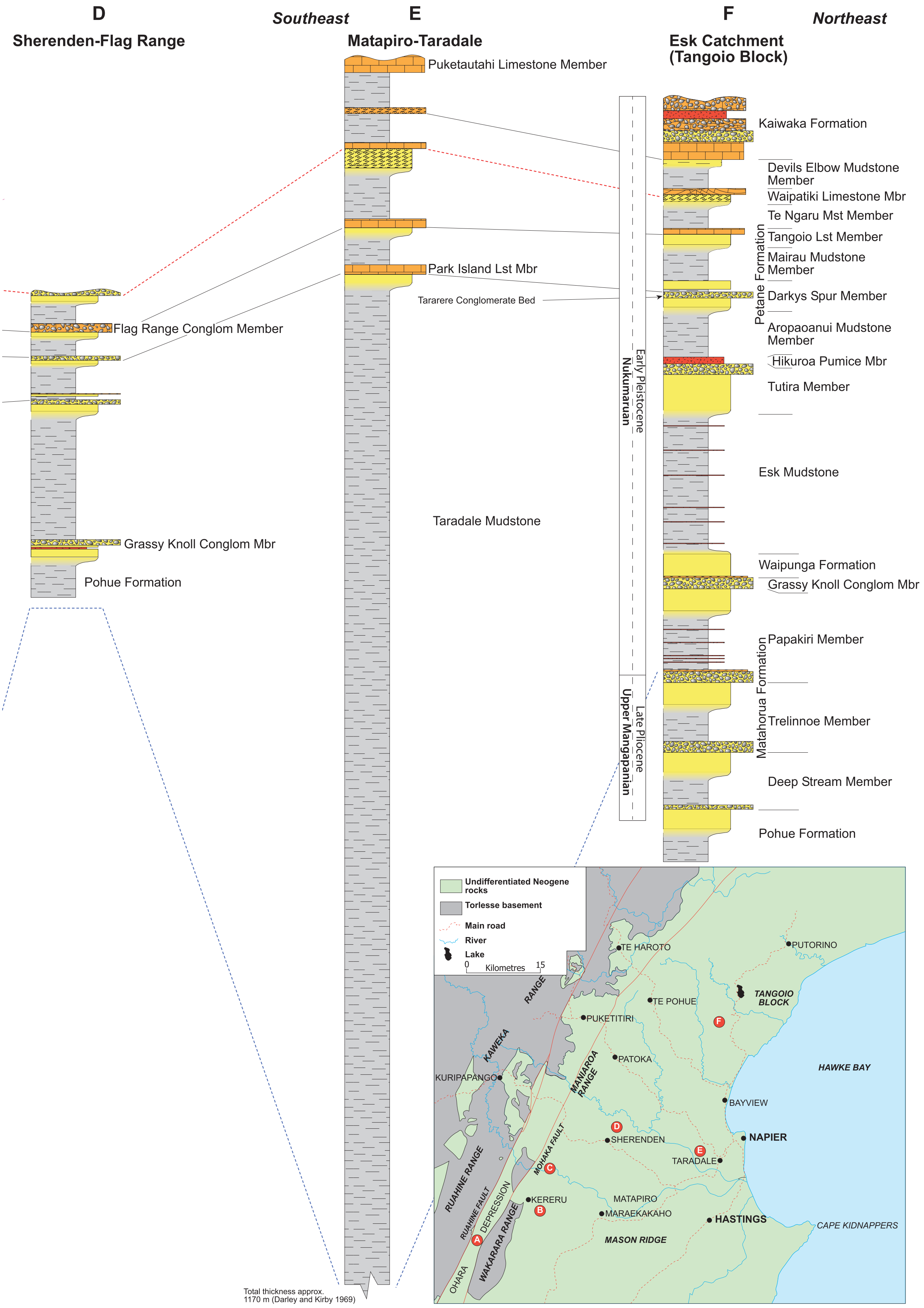


Fig. 18: (Two page spread) Stratigraphic columns of Mangaheia Group and Kidnappers Group in central Hawke's Bay showing in particular the distribution of conglomerate facies of late Pliocene (Mangapanian) and Pleistocene (Nukumaruan and Castlecliffian) age.


D
Sherenden-Flag Range
Southeast
E
Matapiro-Taradale
F
Northeast
Esk Catchment
(Tangoio Block)
Puketautahi Limestone Member
Park Island Lst Mbr
Tararere Conglomerate Bed
Flag Range Conglom Member
Grassy Knoll Conglom Mbr
Pohue Formation
Taradale Mudstone
Total thickness approx.
1170 m (Darley and Kirby 1969)
Early Pleistocene
Nukumaruan
Late Pliocene
Upper Mangapanian
Kaiwaka Formation
Devils Elbow Mudstone Member
Waipatiki Limestone Mbr
Te Ngaru Mst Member
Tangoio Lst Member
Mairau Mudstone Member
Darkys Spur Member
Aropaoanui Mudstone Member
Hikuroa Pumice Mbr
Tutira Member
Petane Formation
Esk Mudstone
Waipunga Formation
Grassy Knoll Conglom Mbr
Papakiri Member
Trelinnoe Member
Deep Stream Member
Matahorua Formation
Pohue Formation
Undifferentiated Neogene rocks
Torlesse basement
Main road
River
Lake
0 Kilometres 15
TE HAROTO
PUTORINO
TE POHUE
TANGOIO BLOCK
PUKETITIRI
KAWEKA RANGE
KURIPAPANGO
PATOKA
MANIAROA RANGE
HAWKE BAY
BAYVIEW
NAPIER
SHERENDEN
TARADALE
MOHAKA FAULT
RUAHINE RANGE
RUAHINE FAULT
DEPRESSION
KERERU
MATAPIRO
MARAEKAKAHO
HASTINGS
CAPE KIDNAPPERS
MASON RIDGE
WAKARARA RANGE
OHARA
A
B
C
D
E
F

Matahoura Formation occurrences (Enclosure 2). They indicate that erosion of basement continued into the Nukumaruan and possibly that the area of elevated basement had lengthened to the south (northernmost Ruahine Range).

Poutaki Formation and Kidnappers Group

Conglomerate and associated facies occur within Poutaki Formation of uppermost Nukumaruan (Early Pleistocene) age and Kidnappers Group (middle Pleistocene age), including Salisbury Gravel (Bland and Kamp 2014) (Fig. 18). These units occur mainly south of Ngaruroro River; they form distinct alluvial fans parallel to the range front and are the thickest conglomerate units within the forearc basin (Map Sheets 5 & 6). Conglomerate beds within Kidnappers Group near Cape Kidnappers are detached from the range front, downlap across underlying marine beds of the basin, and were transported via braided rivers as the marine forearc basin in central Hawke's Bay emerged above sea level. We interpret these Early to Middle Pleistocene conglomerate units as resulting from rapid uplift and marked erosion of greywacke basement underlying Ruahine Range.

Interpretation of timing of structure formation from conglomerate facies

Conglomerate clasts cannot be uniquely tied back to sites in the axial ranges. The thin conglomerate beds of Upper Mangapanian age in Puketitiri Formation in Ohara Depression (Fig. 18) can however reasonably be inferred to have been derived from erosion of basement west of Ruahine Fault and/or east of Mohaka Fault in Wakarara Range. This interpretation suggests that these faults along Ohara Depression were active from c. 2.6 Ma, which is within the 3.0 – 2.4 Ma age range implied above from stratigraphic relationships.

The four conglomerate beds within Matahorua Formation were most probably derived from erosion of basement underlying the Ahimanawa Range, forming broad low-angle braided alluvial fans that downlapped shallow marine facies during successive sea level lowstands some 2.52 – 2.36 m.y. ago (Bland etal. 2012). This could have arisen from broad flexural uplift and fluvial incision of basement contemporaneous with differential tilting along the basin margin, as highlighted in the discussion of the structural cross-sections (Enclosure 1). Alternatively, the conglomerate could have been derived from erosion of NISB fault scarpes, dating the minimum Late Cenozoic age of offsets on Ruahine and/or Mohaka Faults.

Conglomerate units within Petane and Okauawa Formations indicate that uplift and erosion of basement was ongoing during the Late Pliocene and Early Pleistocene, building alluvial braid plains into the basin from the range front, probably involving uplift and erosion of Kaweka Range and offset on Kaweka Fault. Accumulation of conglomerate within extensive late-Early and Middle Pleistocene alluvial fans mapped as Poutaki Formation and Kidnappers Group, indicate rapid uplift and marked erosion of Ruahine Range, facilitated by oblique-slip on Ruahine Fault.

Summary

This report describes the broad structure of the forearc basin in central Hawke's Bay, provides details about many of the faults and folds and interprets the timing of formation of these structures. The structures have been mapped on new geological maps of central Hawke's Bay (Bland and Kamp 2014, Enclosure 4, Map Sheets 1-6) and are illustrated on four regional cross-sections (Enclosure 1). The North Island Shear Belt (NISB) encompasses a series of sub-parallel reverse and oblique-slip faults lying along the western margin of the basin, partly within basement (notably the Ruahine and Kaweka faults) and partly within the late Neogene succession (notably Mohaka and related faults). The outcrop pattern of the late Neogene units carry no obvious information about the total amount of late Neogene dextral offset on the Ruahine and Mohaka faults, which are probably no more than 10 km and 2 km, respectively. The Late Miocene and Pliocene succession in the south-eastern margin of the basin has been offset by dip-slip reverse faults and uplifted through growth of the inboard margin of the accretionary wedge formed within the Hikurangi margin.

The regional cross-sections reveal the first order structure of the basin. Sections A-A', B-B' and C-C' have very similar overall structure to each other. Important elements are: (i) eastward dip of basement beneath the late Neogene succession, and (ii), uplift (inversion) of the basin margin from at least Upper Opoitian (c. 4.7 Ma) concurrent with continuing sedimentation in the basin axis. Section D-D' (Ohara Depression – Kereru) shows the greatest degree of structure development and amount of reverse faulting. In this south-western part of the basin the axis of the basin is highly oblique to the strike of the main faults (Ruahine and Mohaka faults), resulting in marked offset on faults and basin inversion.

Stratigraphic evidence for the earliest vertical offset on Ruahine and Mohaka faults is inferred from the formation of a significant unconformity between Te Waka Formation and a range of underlying Tongaporutuan to Upper Opoitian units in an area between Ruahine and Glenross faults. These relationships imply Mangapanian (no older than 3.0 Ma) earliest fault offset. Stratigraphic data within Ohara Depression located to the south helps constrain the timing of displacement on Ruahine and Mohaka faults to intra Mangapanian (3.0 – 2.4 Ma). This timing is younger than the Upper Opoitian (c. 4.7 Ma) timing of basin margin tilting evident in Cross-section A-A' and are from stratigraphic analysis. This flexural tilting/deformation may predate the formation of the NSIB.

Thin greywacke conglomerate beds of Upper Mangapanian age in Puketitiri Formation in Ohara Depression indicate that Ruahine and Mohaka faults were active from c. 2.6 Ma, which is within the 3.0 – 2.4 Ma age range implied from stratigraphic relationships to the north. Four conglomerate beds within Matahorua Formation in the northern part of the map area accumulated 2.52 – 2.36 m.y. ago and indicate the timing when basement was clearly being exhumed and being eroded to the northwest of the map area. Clearly this is younger than the Upper Opoitian (c. 4.7 Ma) timing established above for active flexural tilting of the basin margin in this area. Conglomerate units within Petane and Okauawa Formations indicate that uplift and erosion of basement was ongoing during the Late Pliocene and Early Pleistocene, probably involving uplift and erosion of Kaweka Range and offset on Kaweka Fault as well as offset on Ruahine and Mohaka faults. Accumulation of conglomerate within extensive late-Early and Middle Pleistocene alluvial fans mapped as Poutaki Formation and Kidnappers Group, indicate rapid uplift and marked erosion of Ruahine Range, facilitated by oblique-slip on Ruahine Fault.

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